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Increasing the kill effectiveness of High Energy Laser (HEL) Combat System

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SYSTEMS ENGINEERING CAPSTONE PROJECT REPORT

INCREASING THE KILL EFFECTIVENESS OF HIGH ENERGY LASER (HEL) COMBAT SYSTEM

by

High Energy Laser Battle Damage Assessment Team
Cohort 311-133O

March 2015

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A kill assessment system built into a High Energy Laser (HEL) Combat System will provide the U.S. Navy with a method to efficiently engage threats with an HEL effector, improve the weapon scheduling function, and help manage ship's limited power resources. Near real-time Battle Damage Assessment (BDA) and Dwell Time determinations make up the new kill assessment system, which is simply called the BDA System. This system is a critical force-multiplier for ship survivability by limiting all HEL-target engagements to the minimum dwell time required for threat mitigation, while providing a mission kill interface to the Combat System for a calculated decision point to either re-engage the same threat or engage the next assigned target.

This new BDA system concept for a shipboard HEL Combat System was analyzed in order to verify an expected increase in overall system efficiency and performance. The minimum desired increase of threat engagement efficiency was set at 25%. The proof of concept model developed for this project shows that adding a BDA system function to the HEL Combat System causes the system to exceed this threshold of efficiency.

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INCREASING THE KILL EFFECTIVENESS OF HIGH ENERGY LASER (HEL) COMBAT SYSTEM

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ABSTRACT

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LIST OF ACRONYMS AND ABBREVIATIONS

A2/AD	Anti-Access Area Denial
ABL	Airborne Laser
AHP	Analytical Hierarchy Process
AoA	Analysis of Alternatives
AOR	Area of Responsibility
ASCM	Anti-Ship Cruise Missile
ASM	Anti-Ship Missile
ATP	Acquisition, Tracking and Positioning
BDA	Battle Damage Assessment
BOE	Back of the Envelope
BQ	Beam Quality
BTU	British Thermal Units
C2	Command and Control
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance
CEC	Cooperative Engagement Capability
CG	Guided Missile Cruiser
CIWS	Close-in Weapon System
COE	Concept of Employment
COIL	Chemical Oxygen-Iodine Laser
COMNAVSURFOR	Commander, Naval Surface Forces
CONOPS	Concept of Operations
COP	Common Operational Picture
DARPA	Defense Advanced Research Projects Agency
DDG	Guided Missile Destroyer
DEW	Directed Energy Weapons
DEWO	Directed Energy Warfare Office
DOD	Department of Defense
DSB	Defense Science Board
DODAF	Department of Defense Architecture Framework
DT	Dwell Time
DT&E	Developmental Test and Evaluation
EMI	Electromagnetic Interference
EO	Electro-Optical
EO/IR	Electro-Optical Infrared
ESSM	Evolved Sea Sparrow Missile
ET	Electronics Technician

FAC	Fast Attack Craft
FEL	Free Electron Laser
FEZ	Fighter Engagement Zone
FFBD	Functional Flow Block Diagram
FIAC	Fast Inshore Attack Craft
FLIR	Forward Looking Infrared
FOUO	For Official Use Only
ft	Feet
HEL	High Energy Laser
HELEEOS	High Energy Laser End-to-End Operational Simulation
HELMD	High Energy Laser Mobile Demonstrator
HR	House of Representatives
IFF	Identification Friend or Foe
IMN	Indicated Mach Number
INCOSE	International Council on Systems Engineering
IPR	Interim Project Reviews
IRGCN	Islamic Revolutionary Guard Corps Navy
IRIN	Islamic Republic of Iran Navy
ISR	Intelligence, Surveillance, Reconnaissance
JFCOM	Joint Forces Command
JTIDS	Joint Tactical Information Distribution System
KPP	Key Performance Parameter
kW	Kilowatt
LADAR	Laser Detection and Ranging
LaWS	Laser Weapon System
LCS	Littoral Combat Ship
LIDAR	Light Detection and Ranging
LPD	Amphibious Transport Dock
m	Meter
M&S	Modeling and Simulation
MBSE	Model Based System Engineering
MEZ	Missile Engagement Zone
MLD	Maritime Laser Demonstrator
MLRS	Multiple Launch Rocket System
mm	Millimeter
MW	Megawatt
NASA	National Aeronautics and Space Administration
NPS	Naval Postgraduate School
NRE	Non-Recurring Engineering
NSWC	Naval Surface Warfare Center

OA	Open Architecture
OMOE	Overall Measure of Effectiveness
ONI	Office of Naval Intelligence
ONR	Office of Naval Research
OSD	Office of the Secretary of Defense
OT&E	Operational Test and Evaluation
OTH	Over The Horizon
OV	Operational View
PEO	Program Executive Office
P_k	Probability of Kill
QRC	Quick Reaction Capability
R&D	Research and Development
RAM	Rolling Airframe Missile
RCS	Radar Cross Section
RHIB	Rigid Hull Inflatable Boat
S	Second
SE	Systems Engineering
SeaRAM	Sea Rolling Airframe Missile
SLOC	Sea Lines of Communication
SM-2	Standard Missile-2
SoS	System of Systems
SSDS	Ship Self-Defense System
SSL	Solid State Laser
SV	System Interface Description
SWaP	Space, Weight and Power
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle
UCAV	Unmanned Combat Aerial Vehicle
U.S.	United States
USS	United States Ship

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EXECUTIVE SUMMARY

The Navy has a limited ability to evaluate the kill effectiveness of a HEL Combat System. A ship's onboard sensors such as radar, cameras, and personnel, along with off board sensors like helicopters, combat air patrols and other warships in the Area of Responsibility (AOR) provide the Navy's current kill assessment capability. These sensors combine to provide a Common Operational Picture (COP) for situational awareness, and this picture encapsulates the threat kill assessment data. In this setting, an asymmetric threat like a swarm attack may overwhelm a ship's organic sensors, which means that the ship may not be able to maintain the near real-time situational awareness needed to defend the ship. The RAND Corporation defines asymmetric warfare as "conflicts between nations or groups that have disparate military capabilities and strategies" (RAND 2015). Furthermore, swarm describes a tactic where "small distributed units and maneuverable fires converge rapidly on particular targets" and this "scheme of maneuver involves the convergent attack of five (or more) semi-autonomous (or autonomous) units on a targeted force" (Edwards 2000, 1–2). Five or more threats converging on a single ship simultaneously at a rapid rate is a challenging problem for a combat management system. The challenge of engaging a swarm attack with ship's weapons like a Close in Weapon System (CIWS) and a HEL adds another challenge because a Navy warship has finite resources of power and ammunition available to combat the incoming threats. Understanding this problem developed into a desire to maximize the employment of the finite weapon resources in order to maximize the number of kills for a combat management system.

To maximize the number of kills achieved by a HEL during a swarm attack required a systems engineering analysis of laser weapon system designs and equations. A battle damage assessment capability to limit engagement time, or "dwell time," by calculating the time required for the HEL beam to lase the target in order to defeat the threat seemed feasible using probability of kill and lethal fluence.

This concept coupled with the definition of a mission kill could increase the kill effectiveness of a HEL threat engagement. The desire to provide a control mechanism

using battle damage assessment to limit the dwell time of the HEL for a mission kill became the focus of the project's conceptual development and systems engineering (SE) analysis for a new kill assessment capability intended for operations against asymmetric threats. Such a control mechanism could potentially increase the combat system engagement performance, and thereby, increase the survivability of the ship.

In order to better understand whether or not a BDA system was the solution to the swarm threat capability gap, the following key research question became the focus of the systems engineering investigation: *Does a HEL Combat System with a BDA system provide more kills than a HEL Combat System without a BDA system, given a threat scenario or scenarios?*

This research question required tailored SE and systems analysis approaches in order to arrive at an answer within a nine-month project schedule. The selected SE process was Vitech's Top-Down Model Based Systems Engineering (MBSE) method, and the Department of Defense Architecture Framework (DODAF) was the standard for creating the systems architecture. The SE concept of operations (CONOPS) provided a basis for the system requirements, architecture and model. This BDA system concept developed through modeling and simulation (M&S) was not designed for a specific ship platform. This approach was intended to enable the application of the project solution and recommendations to any shipboard combat system.

The BOE and ExtendSim M&S tools were used for the BDA system analysis and proof of concept. The M&S approach included selected operational scenarios and open source data to establish the threat and shipboard weapons data. Using an Analysis of Alternatives (AoA), the threat types and ship weapon types were selected. Baseline ship weapons were narrowed down to one HEL and one CIWS due to system complexity and project schedule. The four asymmetric swarm threat types selected for the scenarios were Fast Attack Craft (FAC), Unmanned Aerial Vehicles (UAVs), Unmanned Combat Aerial Vehicles (UCAVs), and Anti-Ship Missiles (ASMs). The primary threat scenario selected for the model was a swarm attack of all threats in order to stress the system.

The primary tool selected for the M&S approach was the BOE model in Microsoft Excel. ExtendSim was selected as the tool to develop a software model to check the BOE data. The Shipboard HEL 2011 capstone team developed an HEL ExtendSim model that was used as the starting point for the M&S effort of this project.

The BOE analysis clearly supported the recommendation for the integration of a BDA capability. Eight unique scenarios were run 1000 times each to generate an adequate sample for analysis. 50 random threats were used as the inputs to the four unique scenarios. Scenarios 1 and 2 contained one HEL and one CIWS and Scenarios 3 and 4 contained two HEL and two CIWS. Scenarios 2 and 4 removed missiles from the threat set. A HEL Combat System with BDA showed an average kill improvement of 33%, which exceeds the 25% improvement threshold. This proof of concept provides the U.S. Navy with a credible starting point and methodology for further system performance analysis with a more robust model representative of the system interfaces.

Table 1. BDA Kill Results

Scenario (1000 runs each)	HEL	CIWS	BDA	Threat Type	HEL Kill Improvement with BDA (%)	Overall Kill improvement with BDA (%)
1	1	1	Off	All	37	29
	1	1	On	All		
2	1	1	Off	UAV, UCAV, Boat	37	34
	1	1	On	UAV, UCAV, Boat		
3	2	2	Off	All	32	17
	2	2	On	All		
4	2	2	Off	UAV, UCAV, Boat	26	4
	2	2	On	UAV, UCAV, Boat		
Average Improvement					**33**	**21**

List of References

Edwards, Sean J. A. 2000. *Swarming on the Battlefield.* Santa Monica, CA: RAND Corporation. http://www.rand.org/pubs/monograph_reports/MR1100.html.

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I. INTRODUCTION

A. PURPOSE

On 12 October 2000, the USS Cole (DDG-67) was in the harbor in Aden, Yemen when suicide bombers attacked the ship riding an explosive-laden small boat. The resulting explosion killed 17 and injured 39 sailors. The preliminary estimate of repair cost was $243 million and ultimately required 14 months to complete. During this time a national asset was unavailable for international security tasking. The cost of mounting this attack was infinitesimal compared to the cost to the Department of Defense (DOD) and U.S. national security. The low cost of asymmetric warfare had a large impact to the national defense budget, the availability of assets for national tasking, and more importantly the lives of American service women and men. The story of the USS Cole speaks volumes because the asymmetric threat accomplished an effective mission kill with only one small explosive boat. The Navy's ability to maintain freedom of navigation and perform operations in the littorals depends on an ability to counter such asymmetric threats with effective, low-cost weapons like laser weapon systems (Perl and O'Rourke 2001, 1–2).

Existing combat systems detect, track and engage a threat. Employing laser weapons in this combat system framework is challenging because of the speed of engagement, necessary power and cooling resources, and variable weapon dwell time required to defeat multiple naval threats. These naval threats have a wide spectrum of speed and survivability. For instance, missile systems have faster closure rates but are structurally more fragile compared to surface systems such as small boats, which approach slowly but are more difficult to disable or destroy. Potential adversaries have the ability to overwhelm legacy combat systems with low-cost, high-density weapons such as UAV, swarm attacks, ASMs, and suicide attacks by air or sea. With this information in mind, a solution to effectively use a HEL Combat System against known threats for maximum ship survivability needed to be determined and analyzed.

B. PROBLEM STATEMENT

Maritime threats can overwhelm Navy combat systems and thus pose a threat to Naval ship survivability with low-cost, high-density weapons. Therefore, a solution to the problem of effectively utilizing the HEL Combat System to achieve a maximum level of kills was explored. A HEL Combat System is an effective, sustainable, low-cost solution against asymmetric maritime threats since electrical power is the source of ammunition in a Solid State Laser (SSL). The team developed a concept for a BDA system that could be integrated as a subsystem into the HEL Combat System in order to provide a valid method to effectively employ the HEL from a shipboard combat system. An analysis of such a subsystem required a CONOPS and a predictive mathematical model that incorporates a set of threat scenarios, required fluence to defeat those threats, the cycle time of the HEL weapon and an architectural framework through which to incorporate BDA into the combat system.

C. RESEARCH QUESTIONS

The technology readiness of some HEL weapons is increasing. “HEL weapons are currently making a transition from the laboratory to the battlefield. In doing so, all constraints on weapon-system effectives (*sic*) must be honestly evaluated” (Perram et al. 2010, 61). With this in mind, the following research questions were considered:

1. Based the threat scenarios in the proof of concept, against what type(s) of threats will the HEL Combat System be the most effective?
2. How is dwell time calculated for a HEL, and how can this time be optimized for the HEL Combat System?
3. What are the expected cost benefits of implementing the BDA system?
4. Does a HEL Combat System with a BDA system provide more kills than a HEL Combat System without a BDA system, given a threat scenario or scenarios?
5. How would the BDA system be integrated into an existing HEL Combat System?

D. CURRENT STATE OF HEL ON SURFACE SHIPS

HEL weapons are progressing towards implementation on certain Navy vessels because they are proving to be an effective weapon against threats in complex, austere AORs such as the Persian Gulf. The USS Ponce recently underwent sea trials for the

Laser Weapon System (LaWS) and was authorized to maintain the weapon onboard for threat mitigation (Lendon 2014). The Office of Naval Research (ONR) Rear Admiral Klunder said "The captain of that ship has all of the authorities necessary if there was a threat inbound to that ship to protect our sailors and Marines (and) we would defend that ship with that laser system. It would be (used) against those (unmanned aerial vehicles), slow moving helicopters, (and) fast patrol craft" (LaGrone 2014). The success of the LaWS program testing onboard the USS Ponce demonstrates that laser weapons are quickly becoming integrated on surface ships to counter enemy threats.

1. HEL Maritime Threat

Multiple short-range maritime threats are eligible for HEL engagement. As was noted in the LaWS testing onboard the USS Ponce, the threat types tested for engagement were UAVs and fast patrol craft (Lendon 2014). These threats are the types that are cause for concern in the Persian Gulf.

2. Surface Ship HELs

The Department of Defense continues to focus on the technological development of specific directed energy weapon types for military operations, which include chemical lasers, solid-state lasers (SSLs) and free electron lasers (FELs) (Perram et al. 2010, 5). Laser weapons classified as solid-state include continuously cooled lasers, heat-capacity lasers and fiber lasers (Perram et al. 2010, 14). The LaWS is one implementation of a fiber solid-state laser that was successfully tested onboard the USS Ponce in the summer of 2014 and approved for operational use (see Figure 1). According to Ronald O'Rourke, a specialist in naval affairs, "a fiber SSL first uses high power semiconductor laser diodes to convert electricity into light. The light then passes through one or more glass optic fibers that contain a small amount of a deliberately introduced impurity or 'dopant' material (O'Rourke 2014, 34). This combination of light and dopant changes the wavelength and concentrates the energy into a narrow beam through the fibers (O'Rourke 2014, 34). In special designs, multiple fibers are combined incoherently (out of phase) to create one powerful beam of energy. The LaWS generates its beam by combining six fiber SSLs incoherently to provide a total power of 33 kW, a wavelength of 1.064

microns, and a beam quality of 17 (O'Rourke 2014, 34). The goal of the LaWS program was to "maximize reliance on existing technology and components so as to minimize development and procurement costs" (O'Rourke 2014, 34).

Figure 1. U.S. Navy LaWS (from U.S. Naval Institute 2014)

The Maritime Laser Demonstrator MLD is a slab SSL that was developed under DOD's Joint High Power SSL program as a rapid demonstration (O'Rourke 2014, 11). Similar to the LaWS, MLD combines lasers to form one powerful beam. Instead of incoherent fiber SSLs, the MLD combines seven slab SSLs to generate a beam with a total power of about 105 kW, which is more than three times that of the LaWS (O'Rourke 2014, 11). This system has undergone multiple maritime test events for the Navy and successfully engaged a small boat in April 2011 (O'Rourke 2014, 11). Following MLD testing, a Navy report determined that the DDG and LCS classes were the most opportune ships to install a SSL weapon system (O'Rourke 2014, 17). Based on this information, SSLs are the optimal laser type for shipboard use and a few SSL types are currently undergoing successful maritime operational testing.

The Free Electron Laser (FEL) is a different laser type than the SSL because of its unique operation. Electrons move through a vacuum while magnets cause them to emit light (Perram et al. 2010, 5). The benefits of FELs are the wavelengths can be tuned to a desired wavelength for atmospheric transmission sweet spots and power can be scaled up to megawatt power levels to counter a wider range of targets (O'Rourke 2014, 24). However, the FEL is not yet a viable option for the Navy because is the system is currently too large for military applications (Harney 2013c, 1035).

Figure 2. Free Electron Laser (from Jefferson Lab News 2006)

Since the LaWS was used in the performance study *High Energy Laser Technology for Navy Surface Combatants*, and since it is the only directed energy weapon system to be approved for operational use on a U.S. Navy ship, the USS Ponce, the HEL selected for this capstone study is the LaWS (Richard et al. 2011).

E. CURRENT STATE OF BDA ON SURFACE SHIPS

BDA or kill assessment is performed rudimentarily using visual and kinematic data. This information is vital to the weapon system in order to stop the engagement activity when a sufficient kill is achieved, which will save any remaining ammunition for subsequent threat engagements. As an example, the CIWS is a stand-alone system that can stop its engagement of a target based on threat kinematic data. The CIWS uses a “shoot-look-shoot” criterion for engagement. Using this logic as a data feedback can certainly provide a means for efficiently using a HEL weapon.

F. PROJECT GOALS AND INITIAL PROJECT TECHNICAL RISK

The goal of this project was to answer the five research questions and add to the body of knowledge for shipboard HEL weapon systems. The technical risks of this project included the ability to properly model the HEL Combat System with a BDA subsystem and a HEL Combat System without a BDA subsystem. Since the focus is on weapon-target pairing and not the complete HEL weapon system functionality, scope selection and system boundaries were critical to the SE analysis approach.

G. PROJECT REPORT OVERVIEW

Chapter II provides a review of existing literature in the field of naval high-energy laser employment. Chapter III describes the SE approach for conceptualizing and analyzing the HEL BDA system and developing a systems architecture for the model. Chapter IV covers the M&S approach for the HEL BDA concept. Chapter V provides the analysis and conclusions from the model. Chapter VI discusses the HEL BDA system integration into the model and an analysis of integrating this new capability on existing ship platforms. Finally, Chapter VII is the conclusion of the report, which offers the project results and recommendations for additional research.

II. LITERATURE AND REFERENCES

A. INTRODUCTION

To establish an unclassified report for the evaluation of a HEL Combat System, the data used for system analysis had to come from open source documentation. Since directed energy, or beam weapons have been imagined for centuries, there were quite a few open source documents and articles available for reference. Advisors provided valuable combat system references and the Internet offered open source data for threat and shipboard weapon analysis. The first step in open source analysis was to determine why directed energy weapons are desired for military applications and then collect any open source references available for evaluation of a HEL Combat System with the integration of a new BDA system.

B. WHY HIGH ENERGY LASERS?

Lasers offer several advantages over conventional naval weapons, chief among them being their near-speed-of-light propagation, long line-of-sight range, very large effective magazine capacity (subject to ship's power and cooling) and low cost per shot. While there are many advantages, there are also many risks to the development of laser weapons for employment on maritime platforms. In 2001 the Defense Science Board (DSB) Task Force on High Energy Laser Weapons Systems Applications concluded, "HEL systems are an area of technological advantage that can be exploited by the United States" but "the United States has underfunded basic and exploratory development research on high-energy laser technologies" (Welch and Latham 2001, 6–7).

Testing of the Airborne Laser (ABL) seemed to pave the way for military applications of directed energy weapons. The ABL program was in development around 2001 using a megawatt-class chemical oxygen-iodine laser (COIL) aboard a Boeing 747–400F aircraft to counter theater ballistic missiles (Perram et al. 2010, 344–345). Testing continued for several years and finally the system had its first successful engagement of a boosting ballistic missile on 11 February 2010 (Missile Defense Agency 2014). Now five years later, the LaWS testing proved successful against short/mid-range maritime threats such as UAVs and small boats onboard the USS Ponce. With authorization to keep the LaWS on the ship as a defensive weapon, the USS Ponce paved the way for directed energy weapon employment on surface ships (Lendon 2014). “Based on progress to date, the Navy could have a fully capable laser weapon deployed within a decade” according to Daniel Goure, Ph.D. (Goure 2014, 1). With this supporting knowledge, the available open source references for concept development and system analysis were explored.

C. AVAILABLE LITERATURE FOR HEL WEAPONS

Implementation of high-energy lasers on a layered ship self-defense system provides a method to counter high-density, low-cost threats with an effective, low-cost countermeasure. Dr. Daniel Goure wrote in *The Next U.S. Asymmetric Advantage: Maritime Lasers to Counter the A2/AD Challenge*:

> The United States Navy is confronted by an expanding array of both qualitative and quantitative threats to its ability to conduct its fundamental missions of forward presence, sea control, power projection ashore and defense of the global commons. The proliferation of advanced, long-range ASMs, particularly when coupled to a robust C4ISR system, is complicating operational planning and could, in the event of hostilities, deny the Navy the ability to operate in critical areas of the world’s oceans. Even individually less capable threats such as fast attack craft and armed unmanned aerial vehicles could seriously drain inventories of defensive weapons. (Goure 2014, 1)

An important research document for the evaluation of a military HEL Combat System is Ronald O’Rourke’s “Navy Shipboard Lasers for Surface, Air, and Missile Defense: Background and Issues for Congress” (O’Rourke 2014). The body of the document discusses the advantages and disadvantages of deploying lasers aboard naval vessels and the appendices describe the proposed laser types that have been considered thus far in detail. In the area of BDA research, the U.S. Joint Forces Command (JFCOM) Joint Warfighting Center published the “Commander’s Handbook for Joint Battle Damage Assessment” to elucidate the BDA process. “This handbook is not intended to be authoritative, but is offered as a supplement to extant BDA doctrine. BDA is composed of physical damage assessment, functional damage assessment, and target system assessment.” This publication also provides the various types of intelligence information that weapons platforms employ to determine the effectiveness of engagement (OSD Joint BDA 2004). The three BDA phases described include:

> Phase I—Physical Damage Assessment: Phase I BDA "estimates the quantitative extent of physical damage (through munitions blast, fragmentation, and/or fire damage effects) to a target resulting from the application of military force" (DIA DI 2820–4-03; BDA Quick Guide).
>
> Phase II—Functional Damage Assessment: Phase II BDA "estimates the effect of military force on degrading/ destroying the functional or operational capability of the target to perform its intended mission. The level of success is based upon the operational objectives established against the target" (Joint Targeting School, Combat Assessment Student Guide).
>
> Phase III—Target System Assessment: Phase III BDA is "an estimate of the overall impact of force employment against an adversary target system" (Air Force Publication: 14–210; USAF Intelligence Targeting Guide).

While this reference provided BDA definitions, a specific methodology for a shipboard HEL engagement could not be found. However, using additional references such as *Introduction to Laser Weapon Systems* by Glen P. Perram et al. and *Effects of Directed Energy Weapons* by Philip E. Nielsen, a BDA methodology was determined for analysis. Furthermore, these references also provided information regarding the atmospheric effects of directed energy weapons, including those of a maritime environment.

D. SUMMARY

The literature does not address the subject of BDA methodology for a HEL Combat System specifically; however, there is sufficient information by which a BDA methodology can be derived.

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III. SYSTEMS ENGINEERING AND ARCHITECTURE

A. SYSTEMS ENGINEERING

The systems engineering process started with understanding the stakeholder needs and translating them into system requirements for the system design. The result of the systems engineering approach in this chapter was the development of an operational view (OV) diagram, CONOPS and the system requirements. To reach this outcome, Vitech's Top-Down MBSE methodology is used to create the systems engineering products.

The systems engineering methodology used to develop the BDA system was a modified "top down" approach depicted in Figure 3 (Muehlbach 2014a, 26). Steps 0 and 1 were completed using an evaluation of stakeholder needs, CONOPS definition and system requirements development. Steps 2 through 8 were completed using architecture diagrams including context diagrams, functional flow block diagrams, and IDEF0 diagrams. Step 9 was the model and simulation design of the BDA system and Step 10 was the analysis of the model and simulation data, which included a systems integration analysis. Steps 11 and 12 are not applicable because actual system development is not part of the project. The capstone report and the BDA system model fulfill Step 13 of Vitech's Top Down MBSE process. Using this approach from the view of the overall combat system identified the location and function of the new BDA system to understand the data interactions, functions and interfaces required to develop a proof of concept.

B. STAKEHOLDER ANALYSIS

Step 0 of the Vitech's Top Down MBSE Process is "Define Need and System Concept." A stakeholder analysis was performed in order to identify the BDA system need or requirement, which is also known as the primary function that the BDA system must accomplish. A primary function is necessary to develop an operational view of the BDA concept and a set of system requirements. The process to generate the system requirement included identifying stakeholders, identifying stakeholder needs and performing a stakeholder analysis using the Analytic Hierarchy Process (AHP) pair-wise comparison.

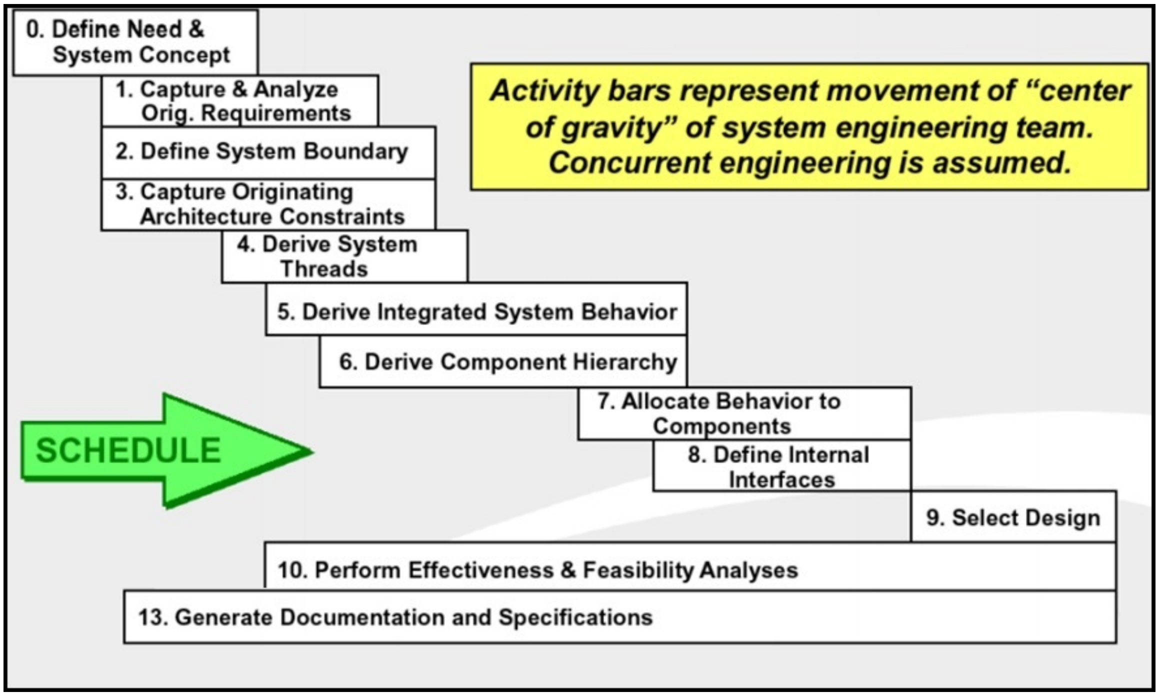


Figure 3. Vitech's Top Down MBSE Process (after Muehlbach 2014d)

1. Methodology

The Raytheon SSDS Program, NPS Systems Engineering Department and Naval Surface Warfare Center (NSWC) Directed Energy were engaged early in the project. The ONR, Code 35 Directed Energy Weapons (DEW) department was also contacted during the first few months to provide their input. The methodologies used to contact stakeholders included in-person meetings, online sessions, emails and phone calls. The needs and requirements were compiled for analysis to determine the priority of the stakeholder requirements. A pairwise analysis was selected as the analysis method to prioritize stakeholder requirements.

2. Stakeholder Requirements

The project Stakeholders listed in Table 1 are categorized as active and passive stakeholders. Active stakeholders described those that were engaged in requirements development, project scope, peer reviews and Interim Project Reviews (IPRs). The Raytheon SSDS Program Office and the Systems Engineering Department at NPS were the active project stakeholders.

The HEL BDA team held meetings with available stakeholders to obtain stakeholder requirements. Raytheon's SSDS Program Office, the Systems Engineering Department at Naval Postgraduate School (NPS), the ONR, and the Direct Energy Program Office at NSWC: Port Hueneme were contacted and utilized to provide input for the requirements analysis. During team meetings with the primary project stakeholders at Raytheon, a definitive project scope and technical need were achieved. The Raytheon stakeholders described a need for a BDA capability on a ship combat system.

3. Identify Needs

At the outset of this project, a meeting was held with Raytheon lead engineers in order to determine gaps or needs in a shipboard combat system. Immediately, the need for a BDA capability came up in the discussion and was identified as a technical problem that lacked a systems engineering solution. The team determined that this was a need that could be applied to a combat system with an HEL. With this project scope in mind, a design concept could add to the body of knowledge of shipboard combat systems as well as DEW. A follow-on meeting with ONR stakeholders from Code 35 Directed Energy Weapons provided a great opportunity to share the project scope and goals and to also receive input for the employment of the HEL BDA concept. Project advisors each supported the systems engineering process of the capstone project and held weekly meetings with the HEL BDA team.

4. Stakeholder Analysis and Requirements

The team leveraged an AHP pair-wise comparison analysis to identify the priority of stakeholder needs for the BDA system (Manalo et al. 2014). An AHP pair-wise comparison is a tool used for weighting several criteria two criteria at a time (Triantaphyllou and Mann 1995). This mathematical tool is a great method to decide which system top-level functional requirements are the most important to create the system design. This information is provided through weights of importance that are output from the AHP pair-wise tool. Using an input weighted system of each requirement with stakeholder rankings of either a 3 or 4 for low and high importance out of the group of requirements, the output is automatically generated. In this manner, the tool provides a rank of the top-level functional requirements amongst the list of requirements by normalizing each pairing to one. A great example of the AHP pair-wise analysis is found in the *International Journal of Industrial Engineering: Applications and Practice*, Vol. 2, No. 1, pp. 35–44, 1995 in the article titled "Using the Analytic Hierarchy Process for Decision Making in Engineering Applications: Some Challenges." Along with the output weightings is a bar graph that provides a view of the final rankings or weights of the five main stakeholder requirements for the BDA system.

Table 1. HEL BDA Stakeholders

Stakeholder	**Category**	**Goal/Need**
Raytheon SSDS Program Office	Active	Develop additional Battle Damage Assessment (BDA) capability for the Ship Self Defense System and integrate the High Energy Laser (HEL)
Systems Engineering Dept., Naval Postgraduate School	Active	Employ a Systems Engineering process to develop additional Battle Damage Assessment (BDA) capability for the U.S. Navy Combat Systems and integrate the High Energy Laser (HEL)
Office of Naval Research	Passive	Provide information for swarm/UAV raids
Navy Program Office, Aegis	Passive	Provide oversight and input for updates to the Aegis to incorporate BDA algorithms and CONOPS
Navy Program Office, SSDS	Passive	Provide oversight and input for updates to the SSDS to incorporate BDA algorithms and CONOPS
Navy Program Office, HEL	Passive	Provide additional High Energy Laser capabilities and integration information for use in the analysis of BDA with respect to HEL employment
Navy Combat Systems Operators	Passive	Clear CONOPS and training for the use of the HEL and BDA in U.S. Navy Combat Systems
Navy Combat Systems Maintainers	Passive	Maintenance information for the HEL and BDA integrated with U.S. Navy Combat Systems

The functional capabilities for the BDA system collected from the stakeholders include:

1. Determine battle damage for the HEL and other weapon/threat pairs.
2. Calculate dwell time for each weapon system.
3. Be reliable.
4. Be available.
5. Be integrated in a Navy shipboard HEL Combat System.

These five functional capabilities were ranked with the help of Raytheon stakeholders. This set of rankings was used as the input to the pairwise analysis and are summarized in Table 2. The highlighted numbers show the low and high stakeholder weights for each system requirement.

Table 2. Stakeholder Requirements Weighting (after Manalo et al. 2014)

Top-Level System Requirements Weights																		
Increase the kill effectiveness of the HEL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Determine battle damage for the HEL and other weapon/threat pairs
Increase the kill effectiveness of the HEL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Calculate dwell time for each weapon system
Increase the kill effectiveness of the HEL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Be reliable
Increase the kill effectiveness of the HEL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Be available
Increase the kill effectiveness of the HEL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Be integrated in a Navy shipboard HEL combat system

These rankings are put into the input blocks (coordinates [1, 2], [1, 3], [1, 4], and [1, 5]) of the pairwise graph in Figure 5, which serves as a tool to weigh the requirements amongst each other to determine a ranking output. This tool accomplishes this function by comparing the relative value of all requirements then yielding a weighting factor to each one through pairing, which is the origin of the term pair-wise. After inputting the data from Table 2 into the AHP pair-wise comparison spreadsheet, the weights for the top-level requirements were viewed in the bar graph shown in Figure 4. The highest weighted requirement among the five requirements was "Determine battle damage for the

HEL and other weapon/threat pairs" as shown in Figure 4. This requirement became the focus of the project.

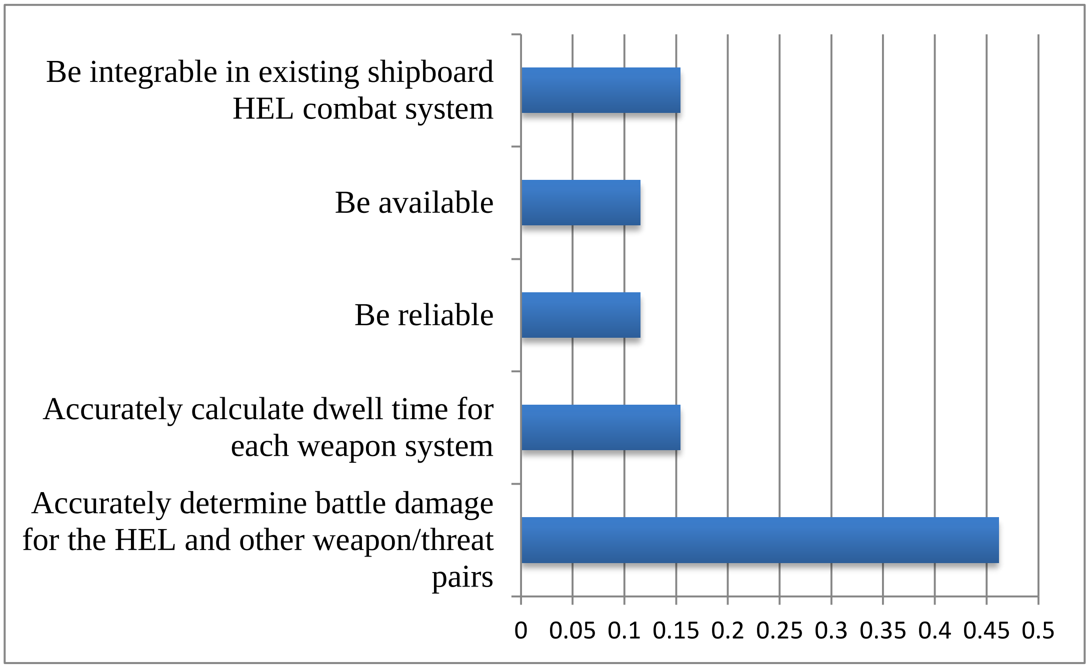
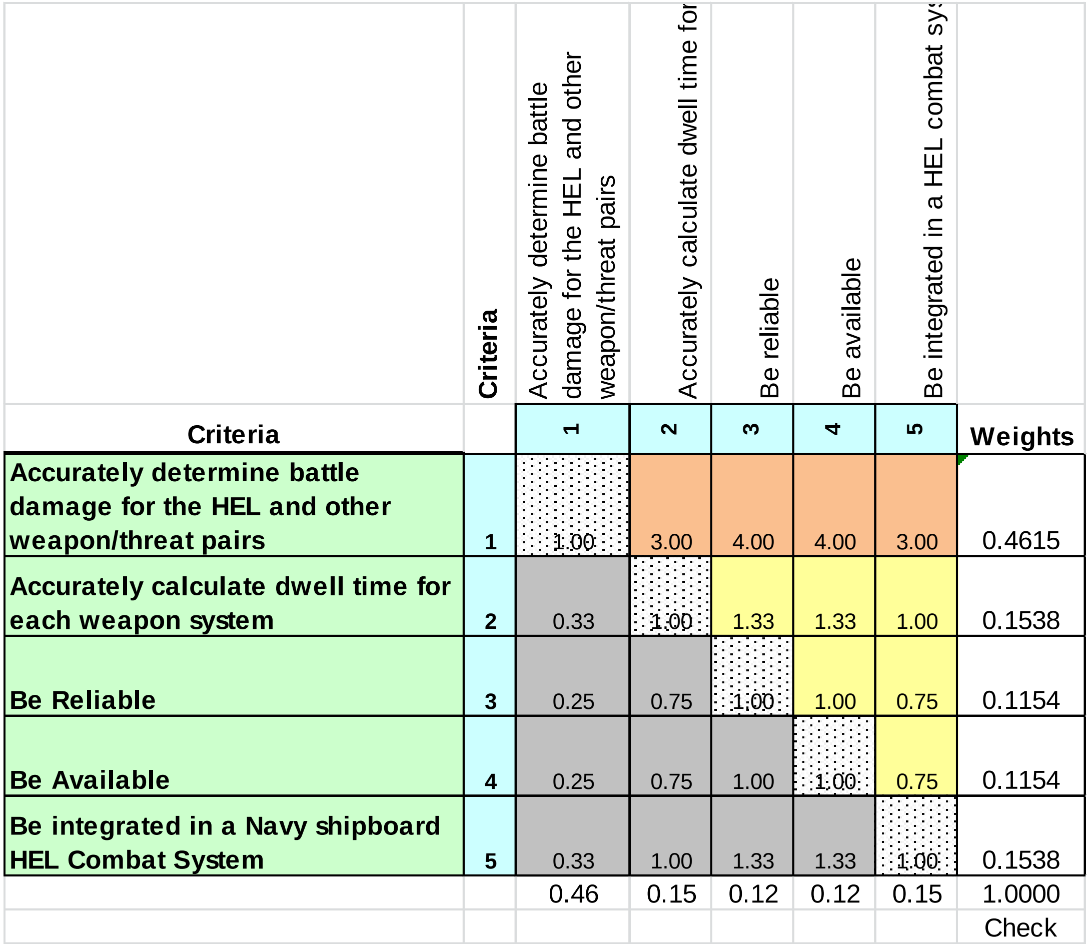


Figure 4. AHP Pair-Wise Requirement Weights

While all five BDA system functional requirements are important to the project, this analysis helped the team focus on the correct requirement and narrowed the project scope. Figure 5 below provides the pairwise analysis performed by the Systems Engineering team.

5. Stakeholder Conclusion

The stakeholders identified the need for a BDA capability in a shipboard combat system. The BDA requirements were developed using the stakeholder requirements for the new battle damage assessment or weapon/threat evaluation capability using a pairwise analysis. This analysis used stakeholder weights for each requirement to yield a priority list of stakeholder requirements. Project stakeholders effectively communicated the technical need and their project requirements, which were compiled and analyzed to achieve the key requirement for the project.



	Criteria	Accurately determine battle damage for the HEL and other weapon/threat pairs	Accurately calculate dwell time for	Be reliable	Be available	Be integrated in a HEL combat sy	
Criteria		**1**	**2**	**3**	**4**	**5**	**Weights**
Accurately determine battle damage for the HEL and other weapon/threat pairs	**1**	1.00	3.00	4.00	4.00	3.00	0.4615
Accurately calculate dwell time for each weapon system	**2**	0.33	1.00	1.33	1.33	1.00	0.1538
Be Reliable	**3**	0.25	0.75	1.00	1.00	0.75	0.1154
Be Available	**4**	0.25	0.75	1.00	1.00	0.75	0.1154
Be integrated in a Navy shipboard HEL Combat System	**5**	0.33	1.00	1.33	1.33	1.00	0.1538
		0.46	0.15	0.12	0.12	0.15	1.0000
							Check

Figure 5. Pairwise Analysis of Stakeholder Needs

C. CONCEPT OF OPERATIONS

With the BDA system need defined, the system concept was developed as part of Vitech’s Top Down MBSE Process Step 0. There are two key functions of the BDA system. First is a near real time BDA to improve the HEL lase time and number of threat kills. The second is calculating the predicted dwell times for weapon/threat pairs to achieve optimal combat system weapon selection for effective and efficient threat engagements. With a capability to determine when a threat is neutralized, the weapon dwell time on a target could be minimized. This allowed the weapon platform to enter its cool down cycle sooner and therefore be ready to engage a new target earlier than the baseline system. The CONOPS showed the capability gap that a BDA system and HEL weapon could fill in current naval capabilities. The section concludes with an overview of the CONOPS that explores the applicability of BDA and HEL to selected threat scenarios.

1. Capability Gap

Combinations of new and old technologies have redefined naval surface warfare in the 21st century. Less concerned with developing expensive blue water fleets, naval powers of the world have pivoted toward the littorals. Coastal combat gives a number of advantages to the nearby host nation. A scenario of particular concern while operating in the littorals of a hostile region is the swarm attack, which overwhelms a naval force with large numbers of high speed, relatively low-cost, deadly threats. Combinations of FAC, UAVs and ASMs pose threats that can quickly exhaust and overwhelm a ship's defensive weapons capabilities. Current defense systems are quickly exhausted and cost much more than the threats they would engage in hostile littoral regions.

Another capability gap that the BDA system fills for a HEL Combat System is the need for automation. To achieve reduced manning requires an allocation of a function previously performed by software. By providing the option for the HEL to receive near real-time BDA during a threat engagement, the HEL weapon with an EO/IR sensor can behave as a stand-alone system with autonomous fires, much like the CIWS. This could potentially reduce manning costs for operation and provide another mode of operation for the swarm engagement doctrine. In the case of the LaWS tested on USS Ponce, the HEL interfaced with the navigation radar and the CIWS. It was also operated independently by operators via an operating station in the combat information center (LaGrone 2014). An automatic mode for a fiber SSL like the LaWS will likely handle a larger number of threats and possibly remove the need for a separate operating console with a specialized operator.

2. Geographic Locations

The majority of world commerce travels via sea lines of communication (SLOC). Nation-states that depend on this commerce have expended considerable resources in order to guarantee their own and their trading partners' access to the seas, particularly narrow chokepoints that connect major bodies of water. The Strait of Gibraltar, Bab-el-Mandeb, Strait of Hormuz, and Strait of Malacca are strategic chokepoints of ever-present concern. The Strait of Hormuz is a narrow waterway through which most of the global petroleum travels by sea (USEIA 2014).

Because of the proximity of transiting ships to hostile coastlines, coastal defense cruise missiles, manned and unmanned aircraft and fast (inshore) attack craft can launch surprise attacks that will overwhelm legacy kinetic defense systems.

a. Narrow Naval Corridors

Hostile littoral regions are the starting point for the HEL BDA CONOPS. Narrow sea lanes, straits or choke points are key characteristics of the sea based economic super highways. For Example, the Strait of Hormuz is 21 miles wide at its narrowest point and it transports a larger volume of crude oil and petroleum products than any other strait in the world (USEIA 2014). These narrow sea-lanes are areas of vulnerability because of the close vicinity of land which results in reduced maneuverability and sensor/weapons posture restrictions. Table 3 lists the busiest chokepoints in the world for the transport of oil products (USEIA 2014).

Upon further investigation of the Straits of Hormuz and the surrounding threats, Iranian forces have the potential to be the most daunting. Based on geographic research, Abu Musa, Greater Tunb and Lesser Tunb are Iranian-controlled islands from which attacks can be launched with little to no warning (USEIA 2014). An Iran and U.S. order of battle is depicted in Figure 6 with a great depth of force on each side (Johnson 2012).

Table 3. Volume of Crude Oil Transit Through Strategic Chokepoints (from USEIA 2014)

Volume of crude oil and petroleum products .transported through world chokepoints, 2009–13. (estimates in millions of barrels per day)					
Location	2009	2010	2011	2012	2013
Strait of Hormuz	15.7	15.9	17.0	16.9	17.0
Strait of Malacca	13.5	14.5	14.6	15.1	15.2
Suez Canal and SUMED Pipeline	3.0	3.1	3.8	4.5	4.6
Bab el-Mandeb	2.9	2.7	3.4	3.7	3.8
Danish Straits	3.0	3.2	3.3	3.1	3.3
Turkish Straits	2.8	2.8	3.0	2.9	2.9
Panama Canal	0.8	0.7	0.8	0.8	0.8
Total Chokepoints	41.7	42.9	45.9	47.0	47.6
World maritime oil trade	53.9	55.5	55.6	56.7	56.5
Percentage through chokepoints	77.4%	77.3%	82.6%	82.9%	84.2%

b. Self-Defense Considerations

HEL weapons systems would augment, but not replace, legacy self-defense systems. The layered carrier air defense begins at the limit of its organic and inorganic sensor range to detect incoming threats. Interceptor aircraft provide the first layer of active defense, operating within and extending the sensor envelope, seeking first to engage striking aircraft and any inbound missiles immediately after launch.

Aegis ships provide a missile engagement zone (MEZ), behind the fighter engagement zone (FEZ), in which they can engage aircraft and missiles that survive the first layer. Standard missiles engage targets at ranges up to 100 nautical miles and speeds greater than 2.5 IMN (1650 knots), theoretically allowing for multiple attacks against a single inbound missile; however, cruise missiles typically closely follow the terrain, in this case the sea surface, and therefore quickly drop below the Aegis radar (SPY-1) horizon.

The final layer of defense is individual ships’ point defense systems, currently composed of the CIWS, rolling airframe missile (RAM), 5”/54 deck gun on cruisers (CG) and destroyers (DDG). HEL weapons systems with BDA could be incorporated into the existing combat systems to provide additional defensive capability against missile swarm attacks that overwhelm legacy weapons (Joint Chiefs of Staff 2014, III-7).

A key capability gap with both Standard missiles and gun-based weapons is their limited magazine capacity. Laser weapons systems do not have a conventional magazine and are instead limited by their ability to create the laser beam. Solid-state lasers represent the additional advantage of reducing the quantity of hazardous materials required on board because they replace conventional high-explosive munitions and lase without dangerous chemicals as in a chemical laser.

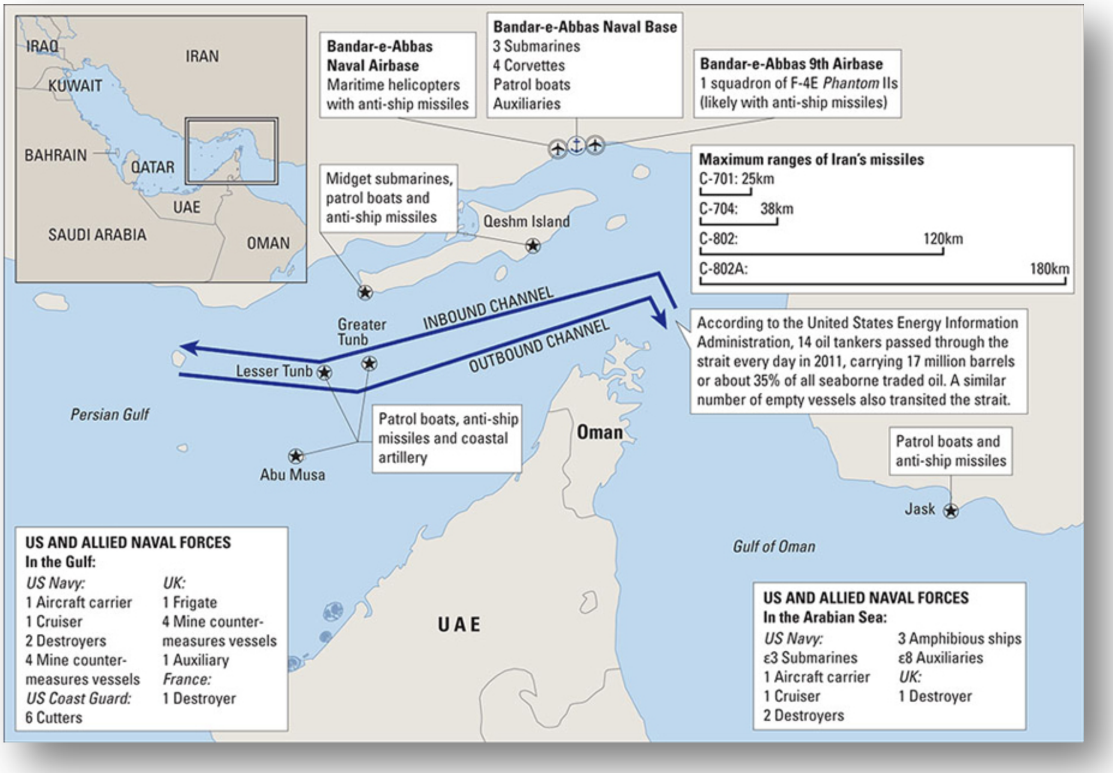


Figure 6. Iran and U.S. Order of Battle (from Johnson 2012)

3. Potential Threats

As depicted in Figure 6, Iran has a layered offensive capability that includes Anti-ship cruise missiles (ASCM), Helicopters/Unmanned Aerial Vehicles (UAV) and patrol boats or Fast (Inshore) Attack Craft (FAC/FIAC). HEL BDA may be an asset to the defense of the ship and her crew against such attacks over a baseline HEL Combat System. The speed, range, radar cross section, elevation, guidance system, weapon load-out and construction material of a threat must all be considered in order to prioritize the threats, schedule weapons and define the battle damage criteria for a mission kill with the HEL.

a. Missile Threat

Table 4 gives specific characteristics of the Exocet and C-802 missiles. These missiles have capabilities similar to other missile threats observed in naval combat. From an operational standpoint, these missiles would generally be launched from a naval or land-based system outside of the range of short or mid-range defense systems.

Table 4. Missile Threat Characteristics (from GlobalSecurity.org 2011)

ASCM	Top Speed	Max Effective Range	Warhead
Exocet AM.39	0.93 IMN	65 km (35 NM)	165 kg
C-802	0.9 IMN	120 km (65 NM)	165 kg

Smaller missiles, with lower fuel stores and smaller explosive yield, may be launched from UAVs and FACs. Missiles launched from UAVs generally travel fast and in straight lines. Disabling these threats requires kinetic impact to cause aerodynamic instability and weakening of the frame of the missile. Stress produced by aerodynamic instability causes a compromise in the structure of the missile and cascades into the projectile breaking itself apart. High Energy Lasers operate under a similar concept as kinetic impact, but instead it softens the missile frame through the application of heat. Lower levels of energy tuned to the appropriate wavelength also provide a capability to destroy sensor systems on a missile. This reduced amount of dwell time to achieve a mission kill of a missile means that the available energy can be used to engage more missile targets. Similarly, UAVs can be engaged by a HEL to achieve a mission kill.

b. Unmanned Aerial Vehicle (UAV) Threat

UAVs are relatively soft targets. Few countries actually operate drones that are on par with the Predator and Global Hawk. Combined with a swarm attack of various weapons, these less capable drones could present a significant offensive threat to surface vessels. Stealth capability has not yet been realized, so UAVs rely on their ability to station themselves well above the range of most weapons except surface to air missiles. Surface combatants with a Standard Missile 2 (SM-2) or higher variant can engage targets at altitudes greater than 100,000 feet but they are very expensive countermeasures for this threat type (Davis et al. 2014, 1–4). To conserve long-range missiles and mitigate cost, a closer weapon engagement is desired, making UAVs a primary target for a HEL weapon. Two recent tests of a Boeing High-Energy Laser Mobile Demonstrator (HELMD) at White Sands Missile Range and Eglin Air Force Base featured 150 successful engagements of airborne targets, including UAVs, with a 10 kW ground vehicle-mounted laser. The deployed LaWS also successfully engaged UAVs demonstrating that UAVs are prime targets for laser weapon systems.

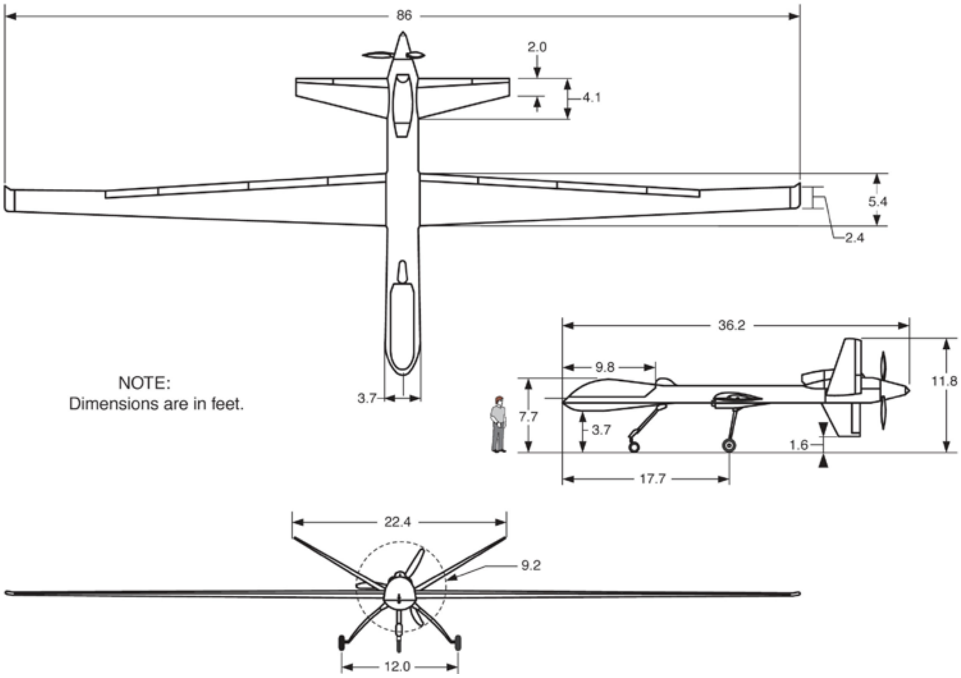


Figure 7. UAV Threat (from NASA 2014)

c. Fast/Inshore Attack Craft Threat

Surface threats range in capabilities from Fast attack/fast inshore attack craft (FAC/FIAC) with simple rigid hull inflatable boats (RHIB) carrying small arms, Multiple Launch Rocket System (MLRS) and explosives, to small warships such as corvettes, patrol boats and missile boats with heavy weapons. Table 5 lists known Iranian surface threats and their respective capabilities.

Table 5. Iranian Fast Attack Craft (from Open Source Intelligence Project 2011, 26–49)

Class	Category	Speed (knots)	Armament
Alvand	Corvette	39	C-802 “Noor” ASM; 324 mm torpedoes
Mowj	Corvette	28	C-802 “Noor” ASM; 324 mm torpedoes; 76mm Fajr-27 Naval Gun
Kaman/Sina	Missile Craft	36	C-802 “Noor” ASM;76 mm OTO-Melara Naval Gun
IPS-18 TIR	Torpedo Craft	52	533 mm torpedoes; C-802 “Noor”ASM
Paykaap (IPS-16)	Torpedo Craft	52	324 mm torpedoes
Bavar (IPS-16)	Missile Craft	52	C-701 “Kowsar” ASM
Zolfaghar (IPS-16)	Missile Craft	52	C-704 “Nasr” ASM
C-14 China Cat	Missile/MLRS Craft	55	TL-10 or C-701 or C-704 ASM; 122mm MLRS
FB RIB-33	MLRS Craft	57	107 mm MLRS
FB MIL-40	MLRS Craft	62	107 mm MLRS
FB MIL-55	Mine/MLRS Craft	68	107 mm MLRS; mines
Ashura	MLRS Craft	45	107 mm MLRS; mines
Kajami	Submersible Craft	40	324 mm torpedoes

According to the “IRGCN Small Boat Tactics” from Office of Naval Intelligence:

> Unlike IRIN tactics-founded on conventional naval operations during the days of the Shah—the IRGCN’s tactics have grown from a combination of irregular warfare and ground force principles. Although the IRGCN has existed for more than 25 years-growing significantly more professional and structured during that time it has eschewed a conventional approach to naval warfare in favor of asymmetric tactics and principles of irregular

> warfare. The results have been adaptable tactics that leverage surprise, speed, maneuverability, mass, and deception, and which ultimately manifest themselves in hit-and-run style attacks. Although public statements from Iranian leadership routinely emphasize their “new” style of conducting asymmetric warfare at sea, IRGCN small boat tactics are neither new nor original but are typical of historical small boat warfare tactics. Thus, in seeking to understand the types of tactics used by the IRGCN, a review of the basic principles and tactics of small boat warfare is essential. (ONI 2009)

Within the geographic region of the Persian Gulf, Iran possesses one of the largest littoral combat fleets. Table 6 is an open-source estimate of available Iranian warships and missile boats from 2010 (Open Source Intelligence Project 2011; Wertheim 2013). The table does not include patrol ships, hovercrafts, submarines, and hundreds of MLRS or mine laying attack crafts, so this list is just a small sample size of the entire fleet of small boats. The data proves that Iran certainly has the capability to present a large swarm threat of fast attack craft in this theater of operations.

Small boat swarm threats are well within the effective range of a HEL. While a single Phalanx CIWS mount will exhaust its 1550-round magazine after approximately 20–30 seconds, HELs have a flexible magazine capacity since it is determined by the ship’s power generation capability. The ammunition is in the form electricity created by generators that are powered by fuel. This is the same liquid fuel used by the LPD 17 San Antonio Class to power its five 2500 kW diesel generators (NavSource Online 2015). As a comparison, there are three 2500 kW gas turbine generators on the DDG 51 Arleigh Burke Class (U.S. Navy 2015) and 4 generator sets on the DDG 1000 Zumwalt Class destroyers (Navsea 2015) that are all powered by the same fuel. Fuel is more convenient to manage than kinetic ammunition, such as missiles since fuel is easily replaced during underway replenishment as fuel transfer. This “HEL ammunition” fuel does not require special storage or handling beyond the holding tanks that are already onboard to meet the ship’s propulsion and power generation requirements. This large shot capacity and low cost per shot makes the HEL a great candidate to close the capability gap against asymmetric swarm threats that include UAVs or FAC/FIAC.

Table 6. Estimated Quantity of Iranian Corvettes and Torpedo/Missile Boats (from Open Source Intelligence Project 2011, 13)

Category	Class	Quantity (estimated)
Corvette	Alvand	3
	Mowj	1
	Hamzeh	1
	Bayandor	2
Torpedo and Missile Boat	Kaman	9
	Sina	3
	Thondor	10
	Tir	12
	Peykaap	20
	Bavar	25
	Zolfaghar	8
	China Cat	10
	Gahjae	5
	Kajami	3
	Mk 13	10
	Tarlan	14
	Dalaam	2
	Total:	138

4. Threat Countermeasures

The U.S. Navy uses a broad range of weapons to counter potential maritime threats. Direct shipboard countermeasures can be grouped into three generic categories to include long, medium and short-range defense. Long-range threats are typically engaged by long-range surface to air missile systems. Medium-range missiles or big-deck guns counter medium-range threats, and finally a wall of ammunition defeats short-range threats by systems like the Phalanx CIWS. The CONOPS considers a typical weapons configuration for a surface combatant including long-range, medium-range and short-range weapons.

a. Close-In Weapon Systems (CIWS)

CIWS was initially developed as a last resort, automated defense system to counter ASMs. This weapon was developed in the 1970s to counter Cold War-era threats.

Recent upgrades address the capability gap for ship survivability against asymmetric and littoral threats. Block 1 improvements added computer systems capable of tracking and targeting missiles exercising advanced maneuvers. Block 1B added a Surface Mode that increased the effectiveness against surface targets by adding a Forward Looking Infrared (FLIR) sensor. CIWS does have its disadvantages, such as accuracy and ammunition magazine limitations, however it is used as a weapon of last resort so a wall of ammunition is exactly the desired effect. In this manner, it is a very effective short-range weapon (Pike 2014).

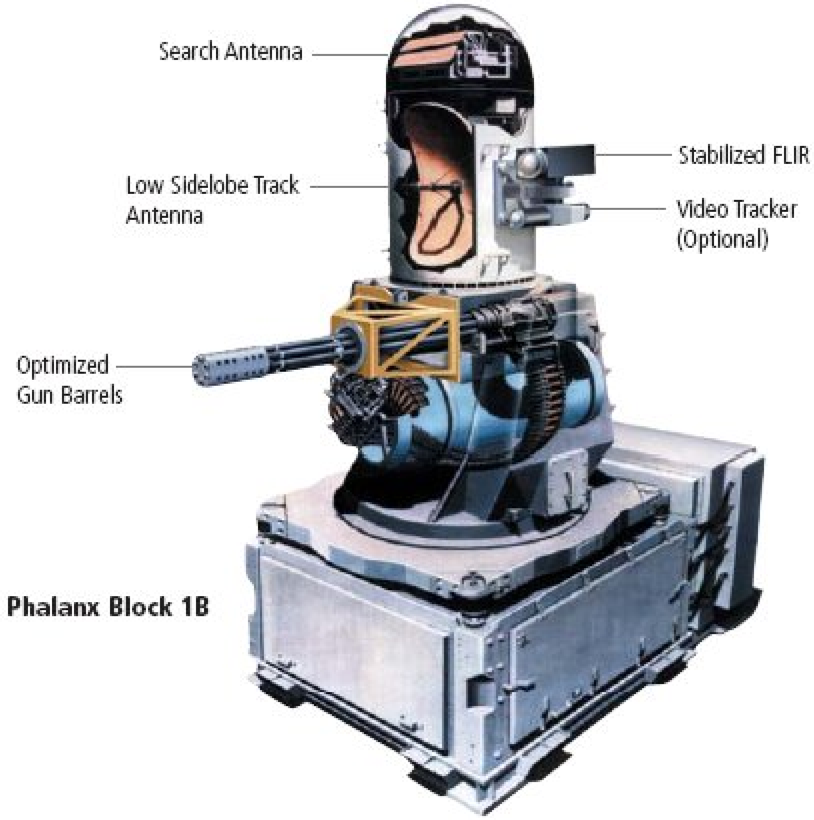


Figure 8. Phalanx CIWS (from MurdocOnline 2006)

b. High Energy Laser (HEL)

HELs are a maturing technology that challenges the traditional kinetic weapon kill method. Current prototypes, such as the Laser Weapons System (LaWS) shown in Figure 10 demonstrate the effectiveness of this system as a maritime defense capability.

A HEL uses power produced by the ship’s diesel generators, main generators or its own power source. In the case of the LaWS, the system is “powered and cooled by a diesel generator independent of the ship’s electrical framework” (Stratfor Global Intelligence 2014). Inherently designed with high availability, the depth of the HEL’s magazine can be measured by the ship’s electrical power generation and cooling capacity.

Because DEWs require a substantial amount of power, a navy vessel is the ideal test platform to support the space, weight and power (SWaP) requirements of a HEL. Clearly, larger ships such as amphibious ships are optimal for HEL installation due to the larger size and space available to support the weapon system. While there are many advantages to a maritime HEL, the issue of beam attenuation or extinction in the maritime environment must be overcome. A maritime environment creates natural atmospheric effects on the HEL energy beam, such as absorption, scattering and turbulence that have to be overcome for trusted performance and reliability during threat engagements (Perram et al. 2010, 209). As the HEL system continues to mature in Technology Readiness Level (TRL) it has already proven to be beneficial against short-range threats during testing on the USS Ponce.

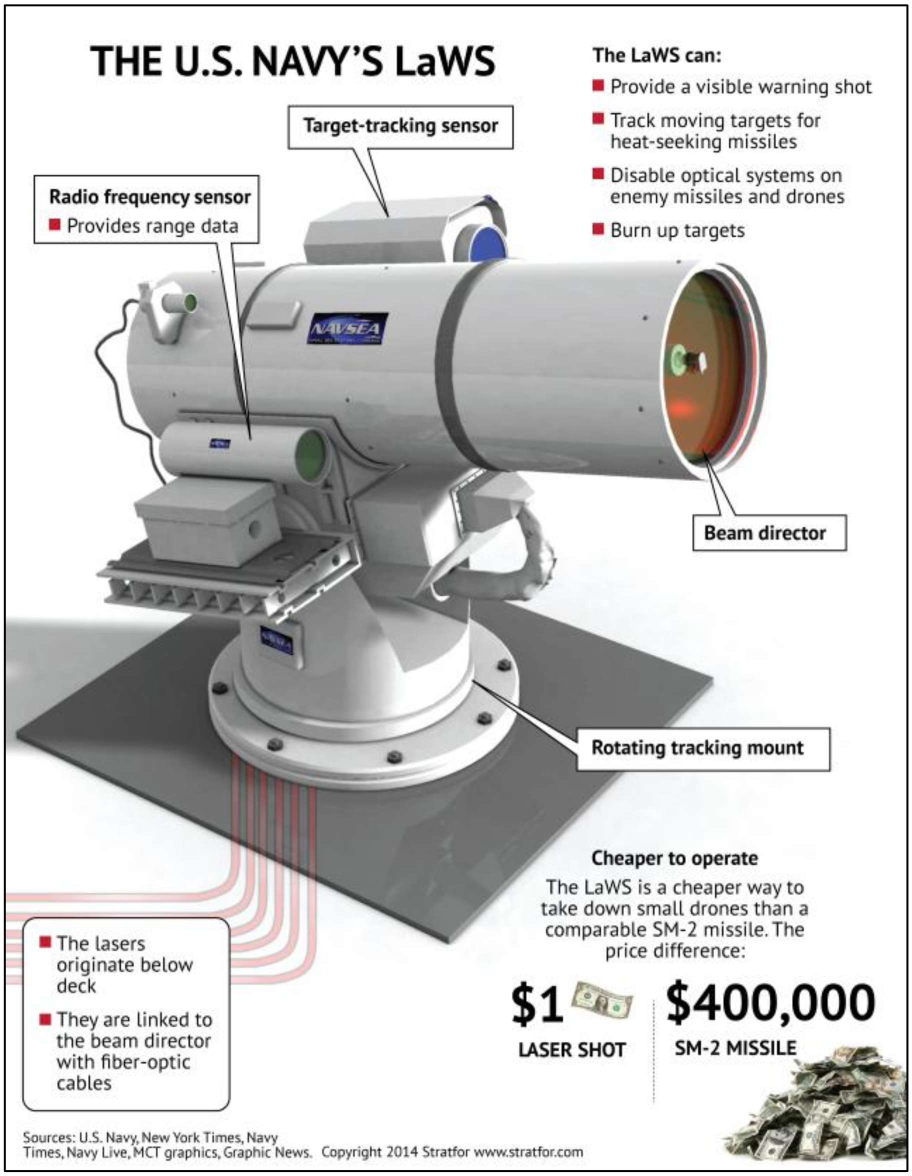


Figure 9. U.S. Navy LaWS (from Stratfor Global Intelligence 2014)

c. *HEL in the Shipboard Layered Defense*

Current Navy strategy uses a layered defense model to manage threat engagements. Figure 10 shows the layered defense concept in terms of sensor and weapon capability ranges in the BOE model. The SPQ-9B has a nominal range of approximately 36 km to provide early threat detection (GlobalSecurity.org 2011c). The detected targets from the SPQ-9B are viewed by the EO/IR sensor at a maximum of 20 km for Recognition processing per Johnson's Criteria, which allows the target to be engaged by the HEL (GlobalSecurity.org 2011c; Harney 2013c). Next, the weapon systems from short/mid-range (HEL) to short-range (CIWS) provide the final two layers around the amphibious transport dock (LPD) for ship self-defense.

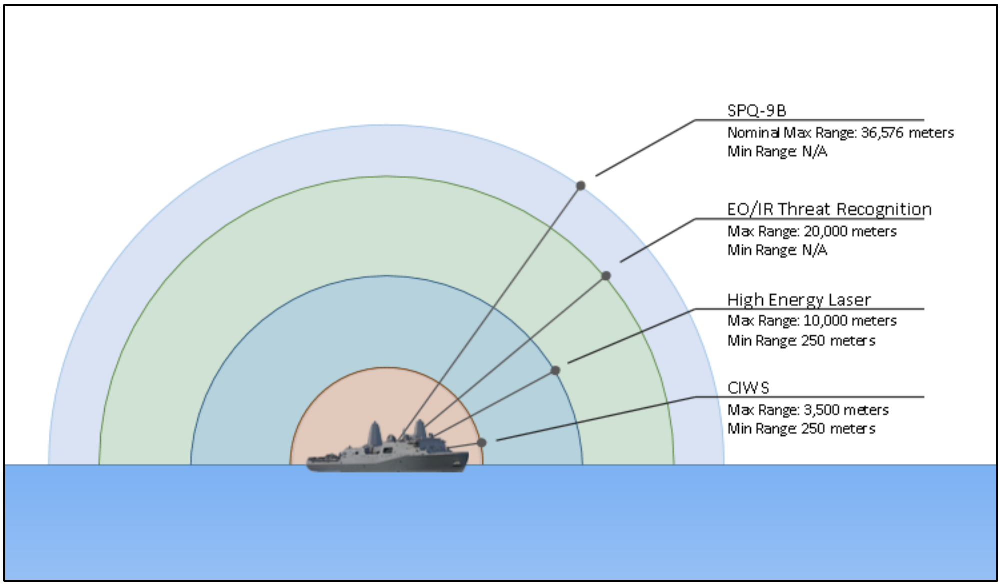


Figure 10. BOE Model Sensor/Weapon Layered Defense Concept (after U.S. Navy 2008)

The missile threat is the closest threat at the start of the threat scenario followed by the UAV/UCAV and finally the small boat threats. The combined BOE simulation data for Threat Scenarios 1–4 provided encouraging data that the BDA system concept definitely adds significant value to the HEL Combat System and is worthy of further research and development.

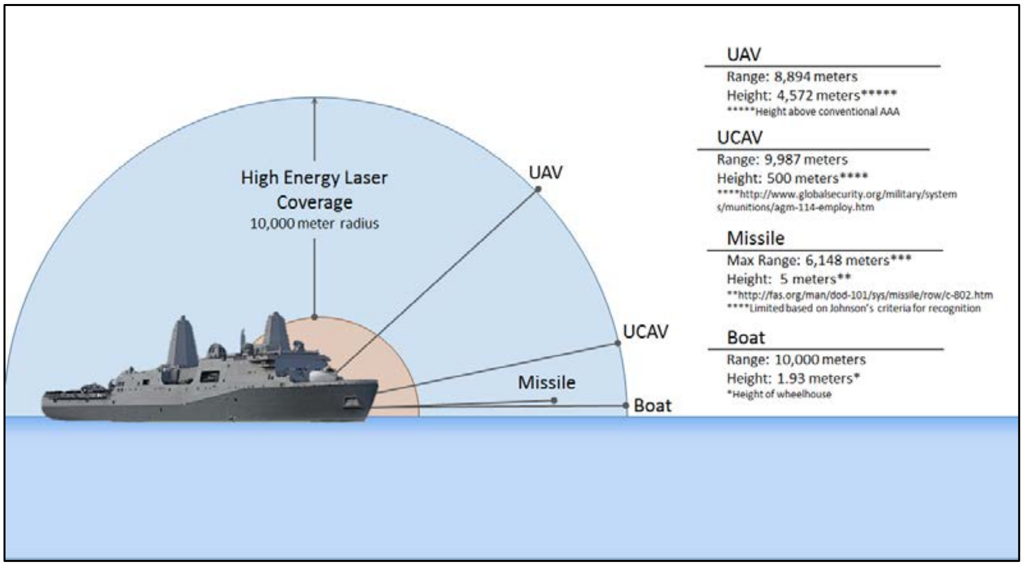


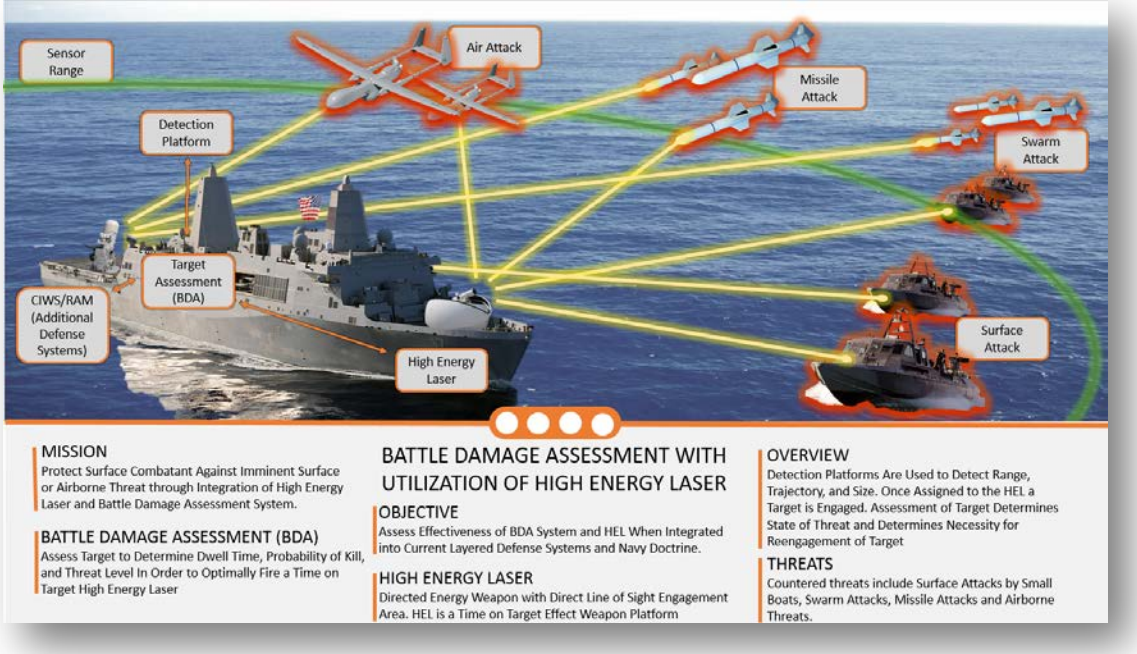
Figure 11. HEL Engagement Ranges (after U.S. Navy 2008)

Similarly, the HEL engagement of the four different threat types in the simulation provided another layered defense concept of the HEL's threat engagement process. Using the BOE model for the range and height data, this chart provides an excellent snapshot of the beginning of the HEL engagement ranges in Figure 11. This knowledge provides a basis for the HEL BDA CONOPS and OV-1 diagram.

5. Operational View

Operational View One (OV-1), in Figure 12, details how a kill assessment system may support a quick and efficient engagement of multiple targets in swarm attack scenarios. In order to accomplish this, the BDA system must integrate with three major systems on the ship: sensors, the combat direction system, and the weapon systems must be able to exchange information in order to realize optimization. BDA would likely reside within the combat direction system to not only receive necessary data for calculations but also to provide the near real-time kill assessment back to the combat system for weapon-threat engagement efficiency.

Detection systems from the weapons platforms, HEL optics and shipboard radar platforms combine to give high fidelity intelligence, surveillance and reconnaissance (ISR) capabilities. This capability provides tracking of azimuth, range, elevation and identification of the target. Automatic identification by the combat system is an increasingly useful capability in that it allows rapid determination of the ideal weapon-target pairing to counter a threat, the required engagement time (dwell time) and real-time assessment of criteria for successful target neutralization criteria. Light detection and ranging (LIDAR), laser rangefinders and other sensors provide high fidelity close range tracking while radar platforms provide long-range tracking including over-the-horizon (OTH) via networked systems to nearby ships, aircraft and land-based systems such as Link-16/Joint Tactical Information Distribution System (JTIDS) (Northrup Grumman 2013, 2–3) and Cooperative Engagement Capability (CEC) (U.S. Navy 2013). The optical systems of HEL are inherently high-resolution telescopes, providing line-of-sight detection that can bridge the gap between visual and long-range sensors without additional equipment. Information from detection systems should provide enough information to achieve an effective target profile. This threat information is critical for a combat management system to intercept and defeat an incoming threat.



MISSION
Protect Surface Combatant Against Imminent Surface or Airborne Threat through Integration of High Energy Laser and Battle Damage Assessment System.

BATTLE DAMAGE ASSESSMENT (BDA)
Assess Target to Determine Dwell Time, Probability of Kill, and Threat Level In Order to Optimally Fire a Time on Target High Energy Laser

BATTLE DAMAGE ASSESSMENT WITH UTILIZATION OF HIGH ENERGY LASER

OBJECTIVE
Assess Effectiveness of BDA System and HEL When Integrated into Current Layered Defense Systems and Navy Doctrine.

HIGH ENERGY LASER
Directed Energy Weapon with Direct Line of Sight Engagement Area. HEL is a Time on Target Effect Weapon Platform

OVERVIEW
Detection Platforms Are Used to Detect Range, Trajectory, and Size. Once Assigned to the HEL a Target is Engaged. Assessment of Target Determines State of Threat and Determines Necessity for Reengagement of Target

THREATS
Countered threats include Surface Attacks by Small Boats, Swarm Attacks, Missile Attacks and Airborne Threats.

Figure 12. HEL BDA OV-1 (after U.S. Navy 2004, 2008 and 2012)

Combat systems identify, prioritize and schedule threats to be defeated by appropriate weapon platforms. By integrating a BDA system, combat systems gain an extra capability to determine the immediate threat to the ship based on target data and kinematics. For example, target types that are hardened against a HEL should be identified by the BDA system. This data will cause the combat system to schedule the threat to the CIWS by the combat system. In general, BDA will use target data and BDA criteria for a weapon-threat pair to provide input to the combat system's weapon-threat scheduling function.

BDA provides inputs to the combat system to maximize probability of kill (P_k) and increase the total number of kills. HEL has unique opportunities for engagement management in that its lasing can be appropriately stopped when no longer necessary. Advanced optics and detection platforms allow the HEL to reduce its lasing time by recognizing the signs of a mission kill. The most practical mission kill for a laser generally results from fatigue in metal due to heat absorption. This softening of the exterior in fast moving objects results in significant structural stress due to aerodynamic instability. Such stresses generally break apart the target resulting in an explosion or the object breaking apart. Other mission (soft) kills may result from sensor blinding (Perram et al. 2010, 332). Boats may experience mission kills through a decrease in velocity or an onboard fire. Recognizing these failure modes by threat type will allow the laser to stop lasing and enter its cool down cycle. Unlike the HEL, the BDA system is not effective for a CIWS.

Test data determined that the CIWS cannot implement BDA because the travel time for rounds from the CIWS to impact the target is extremely short. By the time the leading edge of the salvo reaches the target, the CIWS has stopped firing (Pike 2003).

The BDA system employs modern sensors, recognition algorithms and threat type mission kill data to defend surface combatants. Combat systems, and even specific weapon platforms such as the HEL, inherit an increase in engagement efficiency and effectiveness with at BDA system. This helps to adapt maturing technologies for naval combat in the present operational environment. This new capability allows ships to mitigate more threats for the same amount of power.

6. Summary

Current and future areas of operation require new weapon effectors and engagement techniques to counter relatively inexpensive and disposable asymmetric threat types. In order to provide mission assurance in hostile littoral operating areas, a new BDA capability paired with the unique capabilities of innovative weapon systems, such as the Laser Weapon System may fill critical capability gaps. With the concept of operations defined, the system requirements for the BDA system could be developed.

D. SYSTEM REQUIREMENTS

Step 1 of the Vitech's Top Down MBSE Process is "Capture and Analyze Original Requirements"; therefore, the next step in the systems engineering process was the development of the BDA system requirements. Requirements drive the design needs for the HEL BDA system and provide links between the BDA system, combat system, weapon systems and detection systems on the ship platform. Requirements drive the development of further architectural diagrams, the M&S, systems integration approach and systems analysis method.

1. Methodology

Blanchard and Fabrycky's *Systems Engineering and Analysis* text states that the requirements drive the operational concept by defining the needs necessary to fulfill the mission concept. These needs include the mission's definition, performance and physical parameters, operational deployment or distribution, operational life cycle, utilization requirements, effectiveness factors, and environmental factors. These needs are developed early, carefully, and as completely as possible (Blanchard and Fabrycky 2006, 61).

Developed requirements are used to create a set of Key Performance Parameters (KPPs) that would be used to help shape BDA integration needs and details for the model and simulation conducted at the core of this project. At the end of the BDA Analysis and completion of the M&S phase, requirements are revisited to ensure all objectives and requirements are fulfilled.

2. Requirements Analysis

Requirements have been broken down into four major categories: Weapon System, Shipboard Platform, Combat System, and Detection System. The tables that follow provide the BDA system requirements. Requirements 1.3.1 through 1.3.6 were used to develop the M&S requirements in Chapter IV.

3. Requirements

Requirements were broken down into several sections and subsections as in Tables 7 through 13 below. These requirements outline the needs to appropriately design the software simulation of a Navy surface engagement.

a. Weapon System Requirements

Table 7. Weapons System Requirements—CIWS

1.0.0.0 Weapons System Requirements		
1.1.0.0 Weapon System	1.1.1.0 CIWS	1.1.1.1 Probability of Kill *CIWS shall have a probability of kill for a CIWS engagement per threat type.*
		1.1.1.2 Maximum Range *CIWS shall have a maximum range of 3,500 meters.*
		1.1.1.3 Minimum Range *CIWS shall have a minimum range of zero meters.*
		1.1.1.4 Ammunition Capacity *CIWS shall be restricted to a maximum of 1,500 rounds of ammunition.*
		1.1.1.5 Targeting Inputs *CIWS shall receive target data from the combat system in order to allow for platform precision targeting of a threat.*
		1.1.1.6 Targeting Outputs *CIWS shall be capable of outputting successful or unsuccessful engagement data back to the combat system.*

Table 8. Weapons System Requirements—ESSM

1.0.0.0 Weapons System Requirements (continued)		
1.1.0.0 Weapon System	1.1.2.0 Evolved Sea Sparrow Missile	1.1.2.1 Probability of Kill *ESSM shall have a probability of kill for an ESSM engagement per threat type.*
		1.1.2.2 Maximum Range *ESSM shall have a maximum range of 50,000m.*
		1.1.2.3 Minimum Range *ESSM shall have a minimum range of 1,463m.*
		1.1.2.4 Ammunition Capacity *ESSM shall have scalable ammunition count adjustable by the user.*
		1.1.2.5 Targeting Inputs *ESSM shall receive target data from the combat system in order to allow for platform precision targeting of threat.*
		1.1.2.6 Targeting Outputs *ESSM shall be capable of outputting successful or unsuccessful engagement data back to the combat system*

Table 9. Weapons System Requirements—HEL

1.0.0.0 Weapons System Requirements (continued)		
1.1.0.0 Weapon System	1.1.3.0 HEL	1.1.3.1 Probability of Kill *HEL shall have a probability of kill for a HEL engagement per threat type.*
		1.1.3.2 Maximum Range *HEL shall have a maximum range of 10,000m.*
		1.1.3.3 Minimum Range *HEL shall have a minimum range of 250m.*
		1.1.3.4 Dwell Time *HEL shall control the dwell time on target to destroy or disable each threat type*
		1.1.3.5 Cycle Time *HEL thermal dissipation, energy generation and storage shall be sufficiently large enough to engage large volumes of threats.*
		1.1.3.6 EO/IR *HEL shall utilize EO/IR Sensor to track targets.*
		1.1.3.7 Input Power Requirements *HEL shall have a maximum input power requirement of 1 Megawatt*
		1.1.3.8 Output Power Requirements *HEL shall have a minimum output power requirement of 10% Efficiency.*
		1.1.3.9 HEL Inputs *Inputs shall be received from combat system in order to allow for platform precision targeting of threat.*
		1.1.3.10 HEL Outputs *HEL shall send engagement data to the BDA system in order to allow for analysis of engagement dwell time and to determine the number of successful kills.*
		1.3.11 HEL Outputs *HEL shall send engagement data to the Combat System in order to determine the number of successful kills.*

b. *Combat System Requirements*

Table 10. Combat System Requirements

1.0.0.0 Combat System Requirements	
1.2.0.0 Combat System	
	1.2.2 Determine Target Priority *The Combat System shall determine a target priority list using organic systems.*
	1.2.3 Weapon-Target Assignment (Scheduling) *The Combat System shall schedule available weapons to the target priority list with BDA input.*
	1.2.4 Target Data *The Combat System shall receive threat data from organic sensors in order to determine target type.*
	1.2.5 Target Data *The Combat System shall send threat data to BDA, CIWS and HEL systems.*
	1.2.7 Updated Dwell Time *The Combat System shall use the updated dwell time from BDA to schedule weapons for mission kills.*

c. *BDA System Requirements*

Table 11. BDA System Requirements

1.0.0.0 BDA System Requirements	
1.3.0.0 BDA System	1.3.1 Kill Analysis *BDA shall determine an effective mission kill of a threat based on data gathered from organic and inorganic sensors.*
	1.3.2 Dwell Time *BDA shall determine dwell time for individual weapon systems based on the target profile from organic sensors. This Dwell time can be used to assist the combat system in assigning weapon systems to a threat.*

Table 12. Detection System Requirements

1.0.0.0 Detection System Requirements	
1.4.0.0 Detection System	1.4.1 Target Heading *Onboard detection systems shall detect target heading*
	1.4.2 Target Speed *Onboard detection systems shall detect target speed*
	1.4.3 Radar Cross Section *Onboard detection systems shall detect the target radar cross section*
	1.4.4 Target Profile *Onboard detection systems shall provide data to shipboard systems in order to support the identification of threat types*
	1.4.5 Radar Range *Nominal radar range shall be 20 nm (36,576 meters)*
	1.4.6 EO/IR Range *Nominal EO/IR range shall be 20,000 meters*

Table 13. Analysis and Model and Simulation Requirements

1.0.0.0 Modeling and Simulation Requirements	
1.5.0.0 Modeling and Simulation	1.5.1 Scalability *Models generated shall be capable of being scaled to incorporate weapon systems, threats, and scenarios.*
	1.5.2 Variety of Weapon Systems *Model shall model a layered defense scheme.*
	1.5.3 Simulation Effectiveness *Model shall measure statistics from the engagements that can later be used to conduct an analysis of HEL Combat System effectiveness.*
	1.5.4 Input Data *Model inputs shall be open source, unclassified data.*
	1.5.5 Data Analysis *Model outputs shall provide time-based data for graphical analysis of the HEL Combat System performance*
	1.5.7 Recommendations *The Model and Simulation shall provide data for analysis to determine a recommendation to either include BDA or not to include BDA on a HEL Combat System*

E. SYSTEMS ARCHITECTURE

1. Purpose and Methodology

Step 3 of Vitech's Top Down MBSE Process diagram is "Capture Originating Architecture Constraints" (Muehlbach 2014a). With the requirements established, the next step was to create architecture diagrams in order to understand the architecture constraints of the system, derive integrated system behavior, derive component hierarchy, allocate behavior to components and define internal interfaces, which are steps 4–8 in Vitech's Top Down MBSE Process in Figure 3.

2. OV-1 Diagram

The DODAF OV provides an understanding of system operations through specific actors and provides a description of the tasks, activities, operational elements, and information flows that are necessary to accomplish system operations (Dam 2006, 38). The OV-1 diagram provided in Figure 12 graphically defines the OV of a shipboard HEL Combat System with a BDA capability. This OV is a picture view of the system; therefore, it is an effective starting point to convey the purpose, actors, interactions and operational environment of the system in a manner that is easy understand.

3. Context Diagram

To better understand the intended use and scope of the BDA system as depicted by the OV-1 diagram, a Combat System context diagram was generated. A context diagram is a diagram that defines the boundary between the system, or parts of a system, and its environment. This diagram includes the system interfaces and the general information that is passed between interfaces (Dam 2006, 145). Figure 13 is the Combat System context diagram for this project. In the context diagram, the Combat System is the central system with connections to external interfaces called Sensor Suite, Threat, Weapon Systems and HEL and connected to internal interfaces called BDA and Dwell Time. Initially the central system of the context diagram was a ship system as a whole, however, that diagram did not provide a low-level context to define where the BDA and Dwell Time existed. Changing the central system to the Combat System provided the context needed to understand where and how the BDA systems would exist and interact on a HEL Combat System.

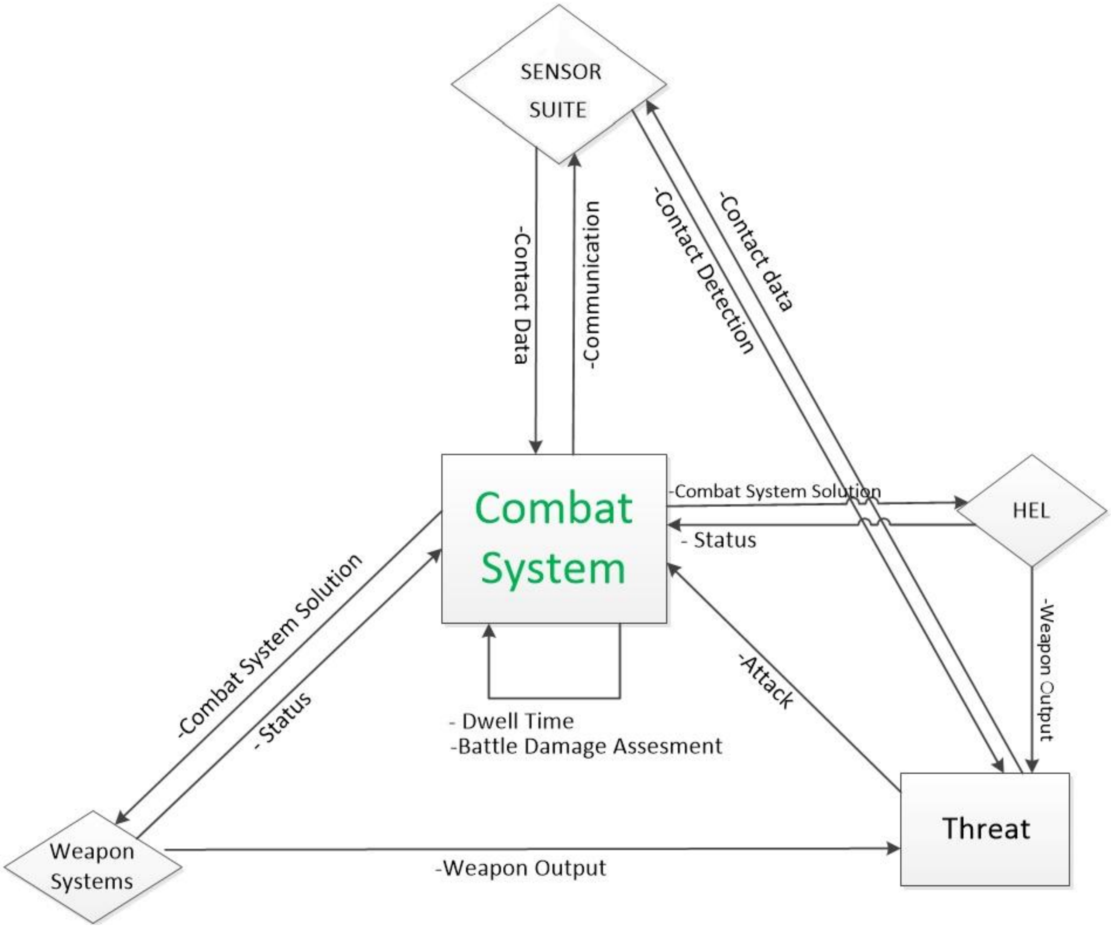


Figure 13. Combat System Context Diagram

All information in the battlespace cannot be transformed into useful data for the combat system to use for targeting threats. The sensor capabilities and limitations represent a technological filter insofar as each specific system only samples a portion of the electromagnetic spectrum. Furthermore, whether the sensor is a passive detector or an active system, raw inputs must meet an internal detection threshold for that sensor to create a track file in the command and control system. Sensor input that does not meet this threshold falls out due to the processing filter. Additional filtering occurs at the operator level due to perceptual, cognitive, and imaginative bias of the man-in-the-loop. Figure 14 provides a simple view of this data filtering concept (Harney 2013a, 14).

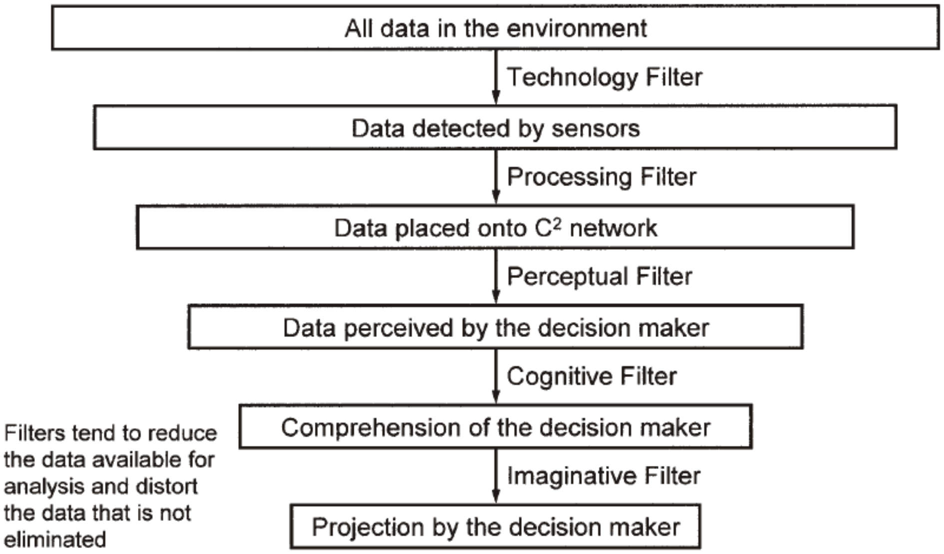


Figure 14. Data Filtering Process (from Harney 2013a, 14)

a. Weapon Systems

Some examples of the weapons on a given ship platform include the ESSM, Mk35 Gun Weapon System and the CIWS. The "weapon output" data line from weapon systems to the threat indicates the weapon-threat engagement. Data to the combat system from the weapon system is the weapon system status message. Data passed from the combat system to the weapon system is the combat system solution with could include items such as the weapon-threat pairing, the fire control solution, and threat data. Figure 15 defines the basic combat system fire control loop to show the interaction between the weapon system and the combat system (control block) for target engagement.

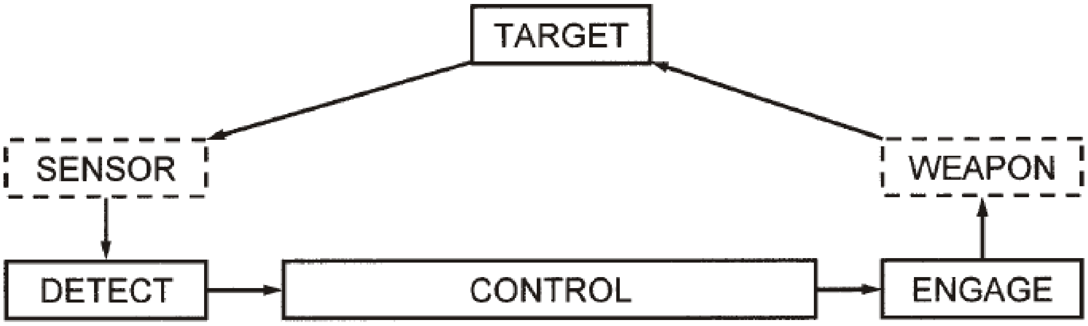


Figure 15. Combat System Fire Control (from Harney 2013a, 7)

b. Threat

Threats include those discussed in section C of Chapter III. These threats are initially detected as contacts by the ship's sensor suite and then given a threat designator in the combat system by either Identification Friend or Foe (IFF) or other source.

c. Sensors

Sensors are the external systems required to detect and track contacts. Common radars and sensors may include the SPQ-9, SPS-73, SPS-48, EO/IR sensors, LADAR, etc.

d. High Energy Laser

The selected architecture is a point-defense system incorporating HEL and Phalanx CIWS; the HEL is the primary weapon system selected to combat threat scenarios. The HEL is separated from the other weapon systems because it is the focus of the analysis and is the primary weapon system selected for the combat system. The purpose of the BDA function is to provide a dwell time solution and kill assessment tool for the HEL threat engagement that will allow a combat system to make effective HEL engagements and offer a decision point to either re-engage the target or to attack a new target. In order to design this concept in the selected architecture, a Combat System FFBD was required as a starting point.

4. BDA Context Diagram

Development of the BDA Context Diagram to link requirements to the BDA system architecture followed definition of the Combat System Context Diagram. Figure 16 is the BDA Context Diagram.

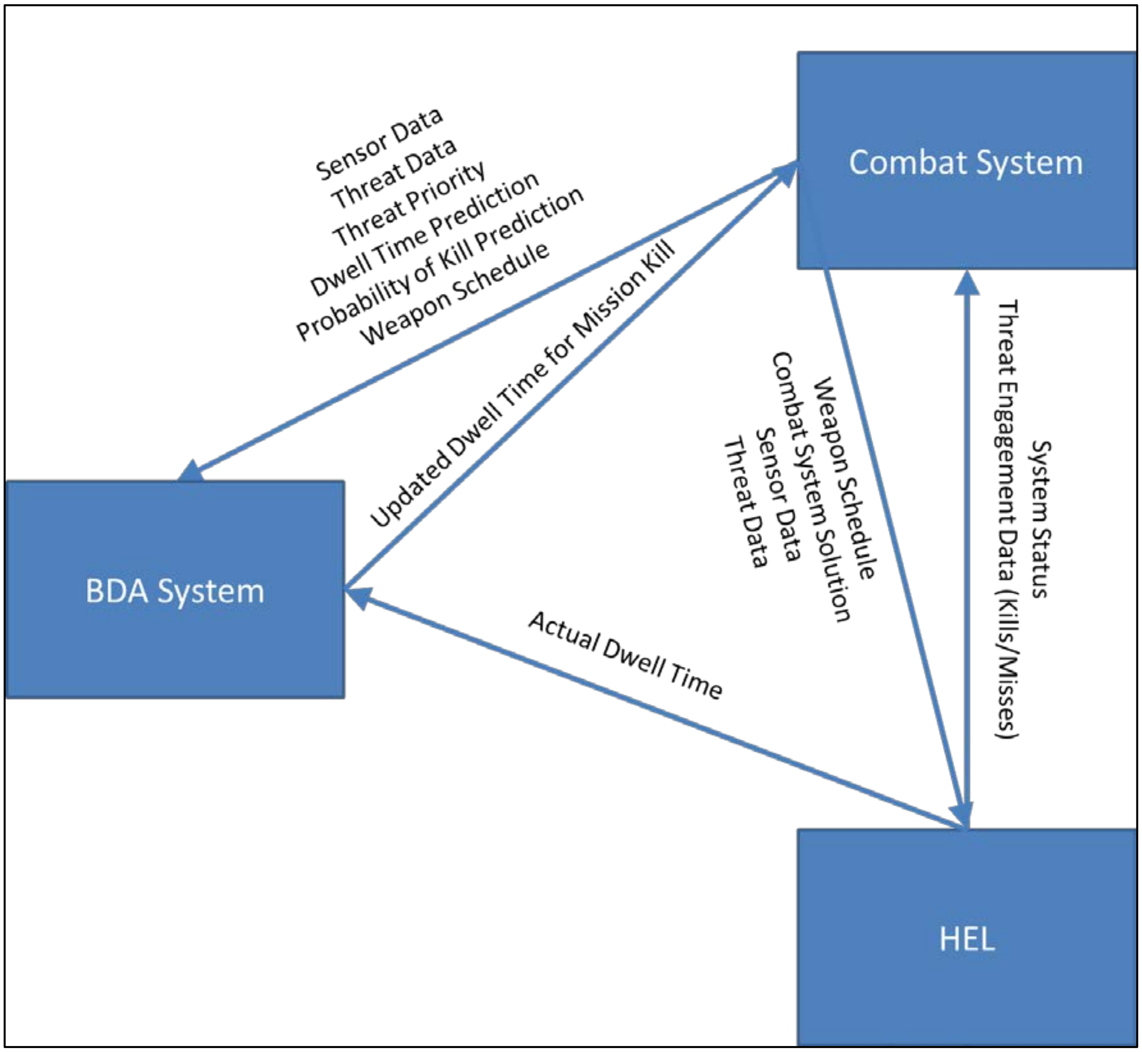


Figure 16. BDA Context Diagram

5. Combat System Functional Flow Block Diagram

A FFBD is a multi-tier, time-sequenced, step-by-step diagram of a system's functional flow. This is also known as the OV-5 or Operational Activity Model in DODAF (Dam 2006, 47). Figure 17 below is the Combat System FFBD that was designed based on our primary Stakeholders' defined needs and system requirements. In sequential order, this flow diagram shows the functions from the time that the target is detected until the time that the target is disengaged. This FFBD provided a functional context view of three new functions: *Predict Probability of Kill*, *Predict Dwell Time*, and *Determine BDA*, which are designated with a black, bold outline. It was important to understand where these functions would exist within the combat system functionality.

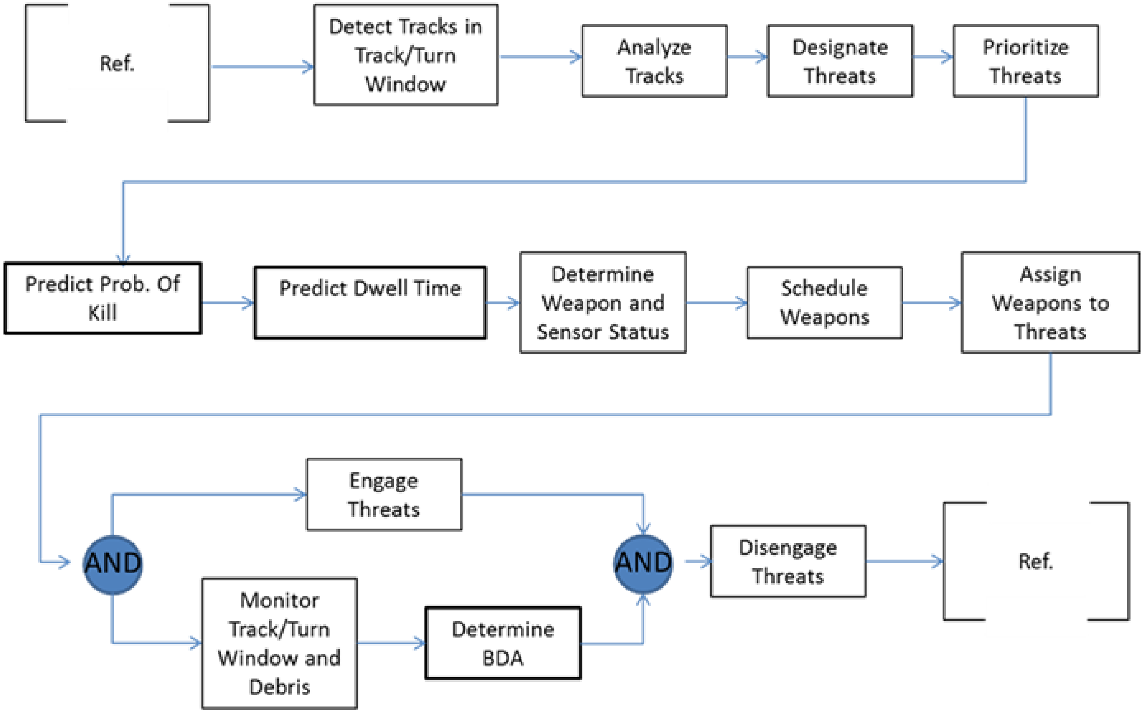


Figure 17. Combat System FFBD

a. *Combat System FFBD Functions*

The FFBD begins with detecting all tracks in a specific track/turn window. Track/turn windows are used to detect, organize and analyze multiple tracks within a complex, dynamic battlespace. Tracks in the window are analyzed for a plethora of data. The bearing, range, elevation and other track data supports a friend/foe designation and threat type designation (UAV, small boat, or missile). Following this determination, the combat system prioritizes the threats for optimal ship survivability. This prioritization function is the input to predictions for the *Probability of Kill and Dwell Time* of each threat and weapon pair. With this input data, the combat system obtains a weapon and sensor status in order to schedule the available weapons and engage the threat. During the threat engagement, the combat system monitors the Track/Turn Window and the target Debris while determining a BDA. This combination of parallel functions is used as a decision point by the Combat System to either reengage the target or engage the next scheduled target(s). The system functions are identified in italics.

6. Predict Probability of Kill and Dwell Time FFBD

Based on the Combat Systems FFBD the prediction of *Probability of Kill and Dwell Time* are key functions in the system of systems (SoS) architecture. Figure 18 is a decomposed FFBD of the prediction of *Probability of Kill and Dwell Time* functions. The combat system prioritizes the threats and this function contains the threat profiles. This threat data received from the combat system is used to simultaneously predict the *Probability of Kill and Dwell Time* and this data is used by the combat system to schedule available weapons. The system functions are identified in italics.

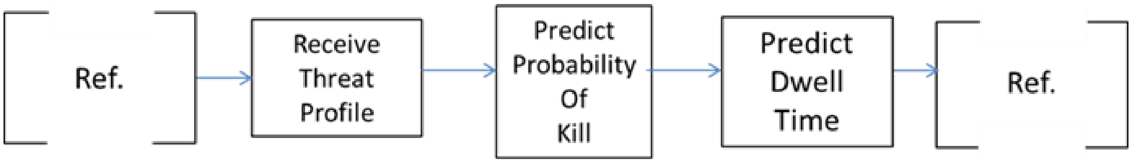


Figure 18. Predict Probability of Kill and Predict Dwell Time FFBD

a. A0 Top Level Function Diagram

Another helpful architecture view is a top-level functional diagram, similar to IDEF0 (Dam 2006, 110). Figure 19 depicts the decomposition of the A0 Top Level Function Diagram for the *Predict Probability of Kill/Dwell Time* functions. This diagram shows the inputs, outputs, mechanisms and controls affecting a system function. The functions are the same as the FFBD but designated as A1, A2 and A3. Function A1 receives Threat Data and Threat Profile Criteria and provides the Threat Type as an output. Threat Profile Criteria and Threat Type are data inputs for the A2 function *Predict Probability of Kill* that provides the P_k as an output. The P_k plus the Threat Profile

Criteria and Threat Data are inputs to the *Predict Dwell Time* calculation, which outputs the Predicted Dwell Time.

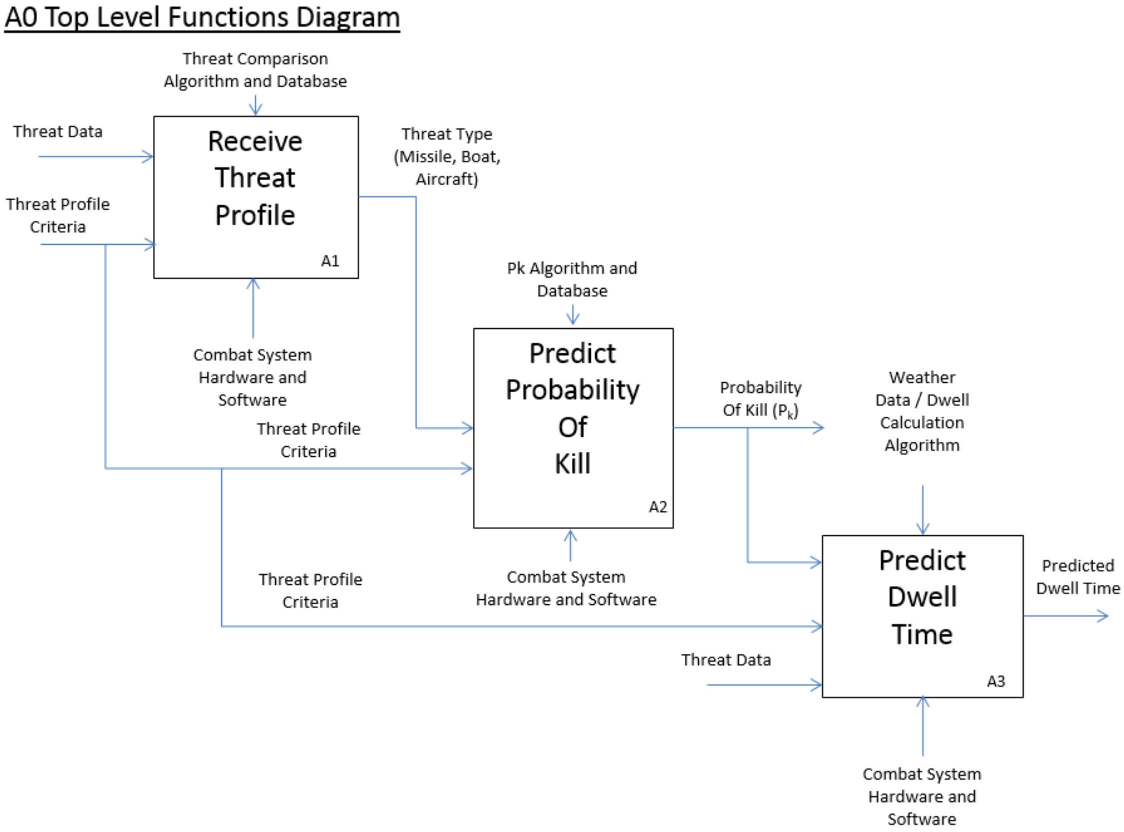


Figure 19. A0 Top Level Function Diagram

b. Lower Level Function Diagrams

The following figures, Figures 20, 21, and 22, further decompose the A1-A3 functions in the A0 Top Level Function Diagram in sequential order. Decomposing the functions provided a means to further analyze the data required for each function at the next lowest level. Understanding the data interactions supported the M&S effort.

Within A1, function A11 compares the Threat Data and Threat Profile Criteria to a database of known threat data to correctly identify a threat with a high level of probability. The identified threat type is stored into a database in function A12.

The *Probability of Kill* sub-functions are similar to the A1 sub-functions with a storage function. The sub-functions are not complex but straightforward. Conversely, the decomposition of A3 is far more complex.

In order to calculate predicted dwell time there are three functions that are performed simultaneously. These functions consist of the *Baseline Dwell Calculation*, *Calculate Atmospheric Effects* and *Calculate Elevation/Range Adjustments*. All three calculations provide input to function A34 *Calculate Predicted Dwell Time*. The *Predict Dwell Time* data is stored in a database and also provided as an output to the next function block.

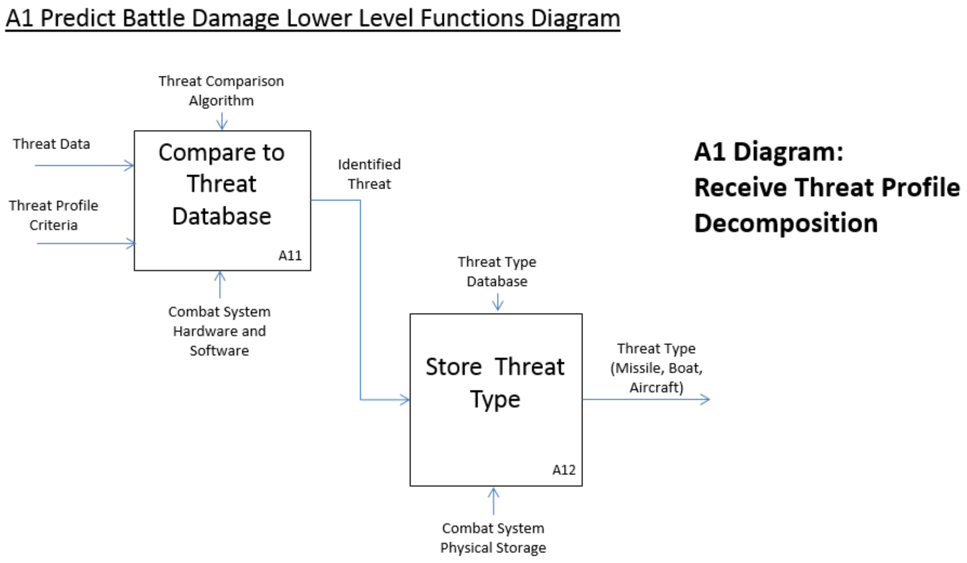


Figure 20. Receive Threat Profile Decomposition

A2 Lower Level Functions Diagram

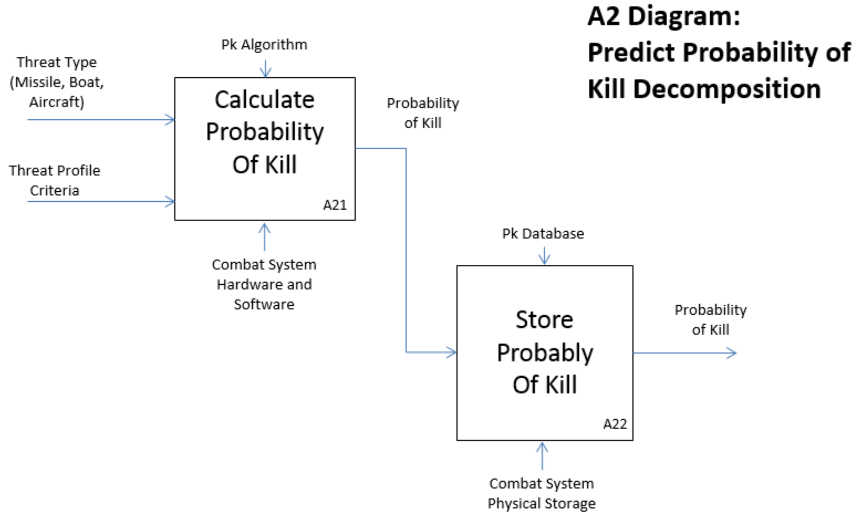


Figure 21. Predict Probability of Kill Decomposition

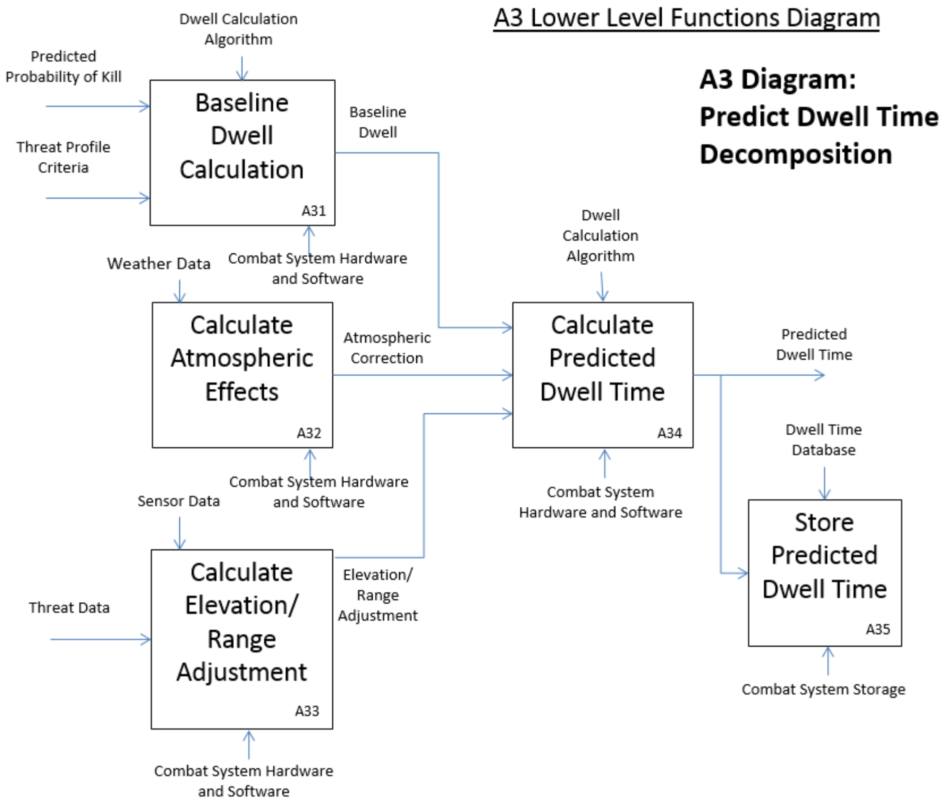


Figure 22. Predict Dwell Time Decomposition

7. Determine BDA Functional Flow Block Diagram

The next new function is *Determine BDA*. The related functions are provided in the FFBD defined in Figure 23 below. The first function *Receive Threat Schedule with Weapon Assignments* is data provided from the combat system. Using this input data, the *Assign Battle Damage Criteria* function assigns a damage assessment method to the weapon-threat pair. After the BDA criterion is assigned, updated data from ship sensors and radars is received in the *Receive Threat Monitoring Data* function. From here, the system *Calculates BDA* and then *Sends BDA* analysis to a decision point where the system either continues to engage the threat or disengages the threat. *Disengage Threats* is the next main combat system function per the FFBD depicted in Figure 18. The system functions are identified in italics in the paragraph.

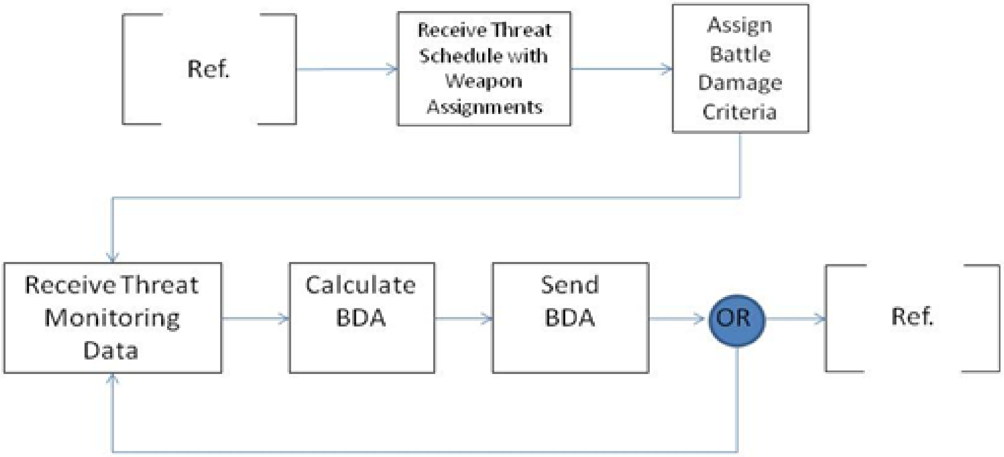


Figure 23. Determine BDA FFBD

a. A0 Top Level Function Diagram

A diagram of the inputs, outputs, mechanisms and controls for the top-level functions was deemed critical to develop the M&S of the BDA functionality. Figure 24 shows the first level decomposition of A0 Top Level Function Diagram for the *Determine BDA*. The top-level functions are *Assign Battle Damage Criteria*, *Calculate Battle Damage Assessment* and *Send Battle Damage Assessment*.

Function A1 receives the Threat and Weapon Pairing data and uses the Battle Damage Database to output the *Battle Damage Criteria Assignment* for the given threat-weapon pair(s). In order to *Calculate BDA*, the BDA Assignment and Updated Target Information are the required inputs, the Predicted Dwell Time and the Battle Damage Database are external controls and mechanisms, respectively. The Predicted Dwell Time comes from function A3 *Predict Dwell Time*. The BDA output is the input to *Send BDA*, which provides the BDA Output Messages.

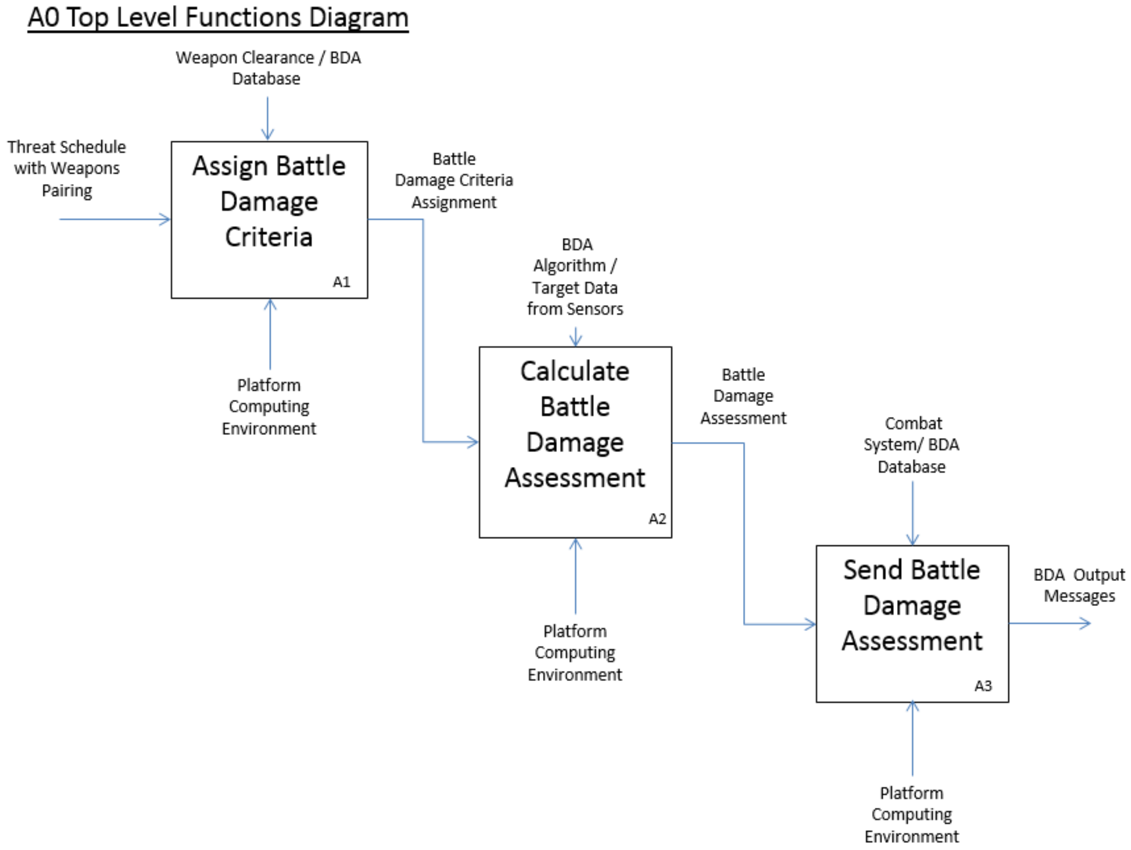


Figure 24. A0 Top Level Function Diagram

b. Lower Level Function Diagrams

To further understand the functions that support a BDA determination, the lower level diagrams for the three major functions were developed and analyzed. This supported the M&S effort for system analysis.

In Figure 25, the threat and weapon pairing information will be sent to A11 from the combat system. Using a BDA database for threat/weapon pairs, battle damage criteria are assigned to the given threat-weapon pair(s) and sent as an output to function A2.

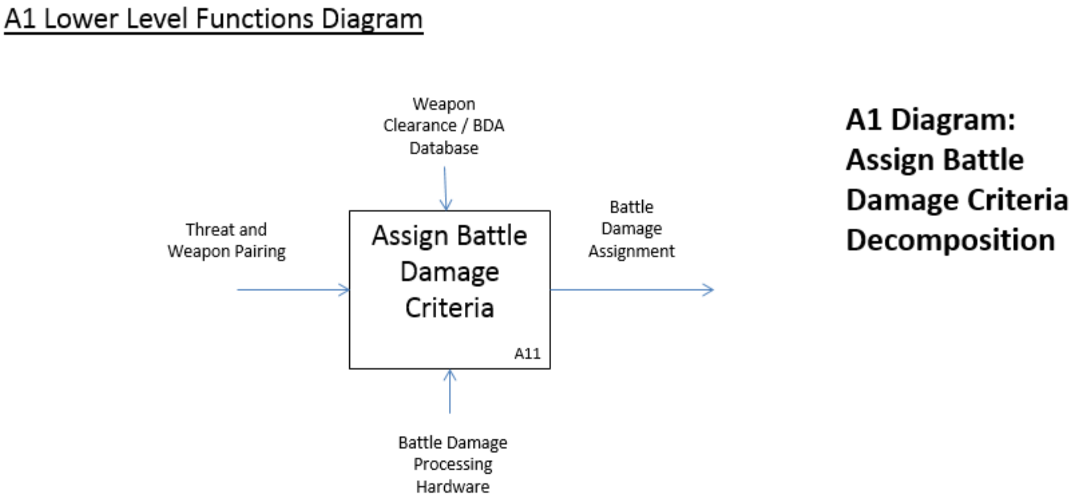


Figure 25. Assign Battle Damage Criteria Decomposition

Function A2 is *Calculate Battle Damage Assessment*, which is further decomposed to *Compute Visual Damage* and *Compute Kinematic Change* (see Figure 26). These functions occur simultaneously using the Target Data as a control. Onboard ship sensors such as radar, LIDAR, cameras and personnel provide physical damage assessment and kinematic change is best detected by a LIDAR or radar. Such sensors also provide the target data to the BDA system. Both of these assessments are provided as inputs to *Calculate Battle Damage* along with a third input called *Battle Damage Criteria*

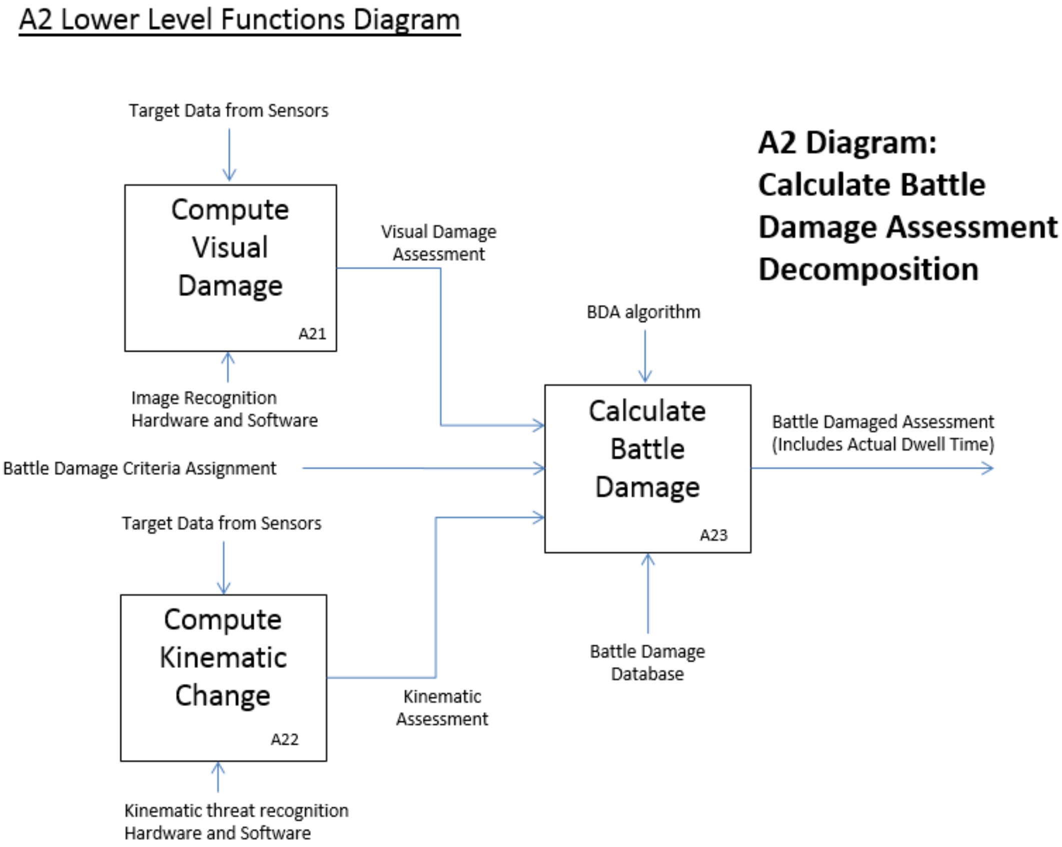


Figure 26. Calculate BDA Decomposition

Assignment, which is provided by function A11. *Calculate Battle Damage* also has a mechanism from the Battle Damage Database to support the BDA determination and a control called Predicted Dwell Time from A3 *Predict Dwell Time* function. This allows the BDA output to include the Dwell Time from the weapon-threat engagement for greater computational accuracy.

The BDA is stored for off-ship engineering analysis. Function A31 provides a notification called BDA Stored to function A32 *Distribute Battle Damage Info*, which distributes the BDA data in the form of BDA Output Messages (see Figure 27).

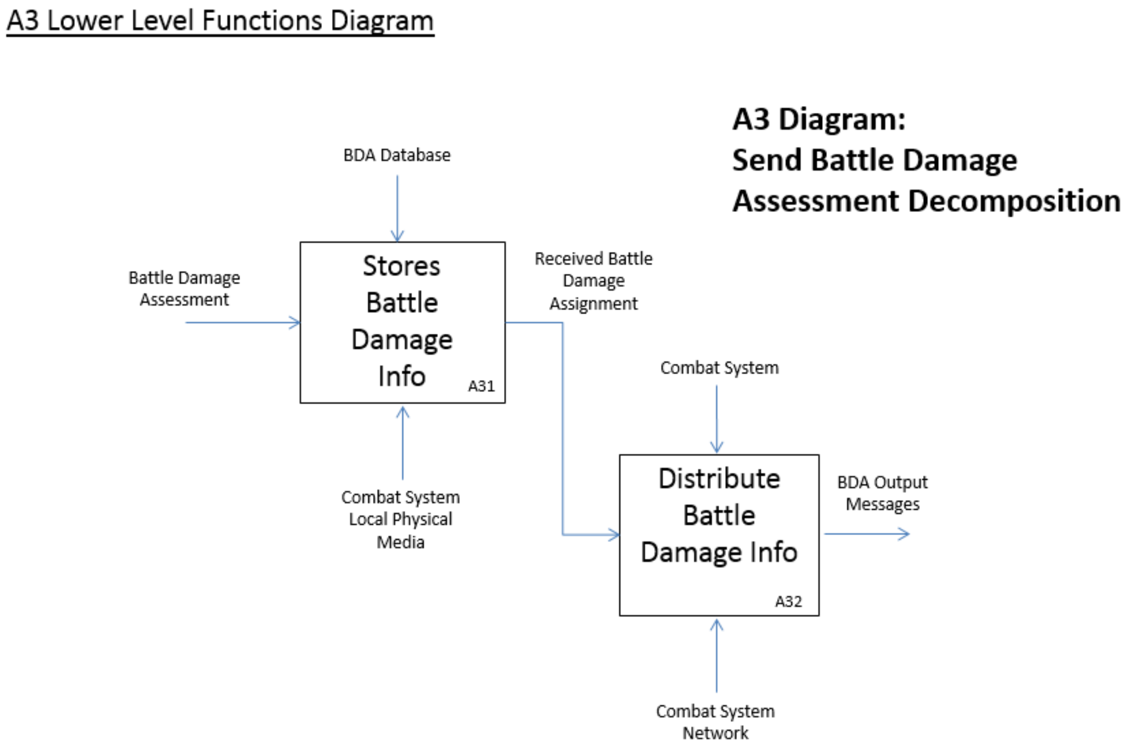


Figure 27. Send Battle Damage Assessment Decomposition

F. SUMMARY

The system architectural methodology used was the “top down” process from DODAF. An OV-1 diagram of the system was illustrated to show the purpose, actors, interactions and operational environment of the system in a manner that is easy understand. A context diagram was provided to better understand the Combat System and BDA system. The FFBDs provided a blueprint for each individual function within a system. From the system FFBDs, top level and lower level functional diagrams were created. These diagrams included inputs outputs controls and mechanisms that helped understand its functions. These diagrams were used to create the BOE model for proof of concept of the BDA system.

IV. MODELING AND SIMULATION APPROACH

A. INTRODUCTION

The next step in the systems engineering process is Step 9, which is “Select Design” per Vitech’s Top Down MBSE Process. The design approach is M&S to achieve a proof of concept of the BDA system. This key step in the systems engineering process included the code design and the system model and simulation development.

B. METHODOLOGY

The methodology used for system verification was M&S methods. Selecting both methods was sufficient for a Proof of Concept approach. For Systems Engineers coding can be a challenging task unless engineers have experience with coding in the selected M&S tools. This detail provided considerable justification for the selection of mathematical M&S tools used for system verification and validation. Based on the team experience, stakeholder input and advisor input, an Excel BOE and ExtendSim were the M&S tools selected for this important step in the SE process.

1. Model FFBD

The approach for the model code design was based a flow diagram designated in Figure 28. This flow diagram provided a high level, visual path forward to build the M&S code in Excel and ExtendSim.

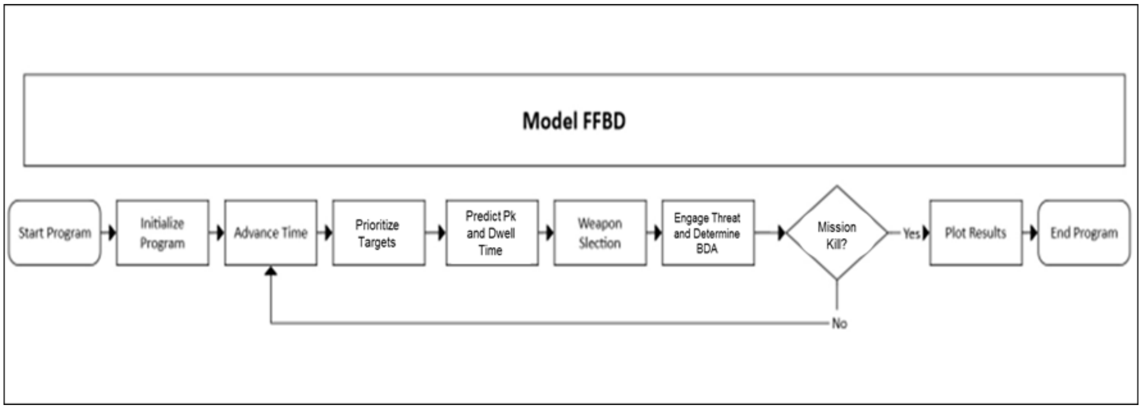


Figure 28. Model FFBD for Code Design

In leveraging the Model FFBD, the next step was to build an Excel model to use as a baseline. This baseline model provided an M&S solution with a high level of detail for the follow on system analysis. It also provided a means to compare data from the Excel Model with the data from the ExtendSim Model. Data comparisons are a good approach to ensure verification of the models. The baseline model developed in Excel will be referred to as the BOE model.

C. BACK-OF-THE-ENVELOPE MODEL

A back-of-the-envelope (BOE) model is a mathematical modeling technique to model discrete events for simulation. For example, in SE3250, Capability Engineering, the class designed a BOE for the "Defense of High Value Targets from Missile Attack" (Pawlowski et al. 2013). This model actually included a similar approach as the HEL BDA solution because of the ship combat scenario against a known set of threats and a given set of countermeasures. The SE3250 model provided a solid technical approach for the HEL BDA baseline model.

1. Basic Model Structure

The BOE model was created to simulate results of 50 random threats attacking a ship with layered defenses. The model has the capability to use ESSM, HEL and CIWS to defend itself. For the purposes of this analysis the missile capability was turned off in order to more closely approximate the installation on a ship like the LPD 17 class which does not have vertical launch capability (U.S. Navy 2014a). Combatants such as DDG 51 and DDG 1000 classes (U.S. Navy 2014c) have VLS with large complements of SM-2 interceptor missiles. Figure 29 shows the basic flow through the model. Initially 50 threats of random type are created. These threats can be any of the following: missile, UAV, UCAV and boat. The selection of the data for each of these threat types is detailed in section D.2. After the threats are created the distance to the ship is determined using the basic radar equation and the threat radar cross section (RCS). The engagement priority for each threat is determined and then they are sorted based on that priority. The threats are then engaged first with the HEL and then with the CIWS if the HEL misses or cannot engage due to a time limitation.

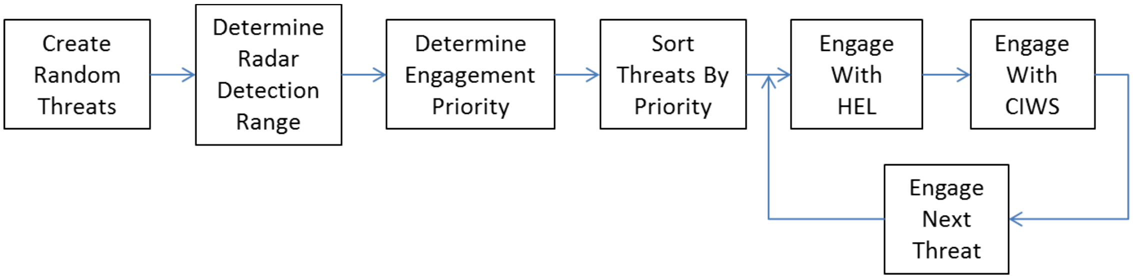


Figure 29. BOE Model Flow

2. Setting Variables and BOE Data

Multiple variables were required for the BOE model. Appendix C contains data used in the BOE model, including variables, threat data and ship countermeasures data. An AoA was performed on the threat data and ship countermeasures data in order to complete the variables for the BOE model. All data referenced in Appendix C is open source data.

a. Threat Data Analysis of Alternatives for BOE Model

The threat types that were decided upon to represent long-range, mid-range and short-range threats from the CONOPS, which included ASMs, UAVs, UCAVs and small boats (FAC/FIAC) in the Persian Gulf theater of operation. The following key threat attributes or variables were analyzed for alternatives:

- Speed (meters per second)
- Range (meters)

Based on the research contained in Appendix A, specific threat types were identified to complete the set of variables in the BOE model. The alternatives discovered for each threat type are provided in Table 14.

Table 14. Threat Type Options for BOE Model

Threat Type	#1	#2	#3	#4	#5	#6
ASMs	Noor-2 (C-802)	Kosar	Nasr	Harpoon		
UAVs/UCAVs	Mohajer	Ababil	Ra’ad 85	Yassir	Karrar	Fotros
Small Boats (FAC/FIAC)	Kaman/SINA Class	Thondor Class	C-14 “China Cat” Class	Kajami Class	IPS-16	

(1) Anti-Ship Missile Selection

Data for the ASM threats was compiled into Table 15 and analyzed for implementation in the model. According to a House of Representatives Report, the C-802 anti-ship cruise missiles are “a threat to our national security” and “place the safety and security of American servicemen and women stationed in the Persian Gulf theater of operations at risk” due to their sea-skimming and nearly-supersonic capabilities (U.S. House 1997, 1).

> In November 1996, Iran conducted land, sea and air war games in the Persian Gulf and the Gulf of Oman and successfully test- fired a C–802 anti-ship cruise missile from one of its patrol boats. Admiral Scott Redd, the former commander-in-chief of the United States Fifth Fleet stationed in the Gulf, said that the C–802 missiles give Iran a “360-degree threat which can come at you from basically anywhere.” Deputy Assistant Secretary of State Robert Einhorn told the Senate Governmental Affairs Committee on April 11, 1997, that the C–802 cruise missiles “pose new, direct threats to deployed United States forces. (U.S. House 1997, 2)

Based on this research, the Iranian Noor-2/Chinese C-802 missile was selected as the ASCM to implement in the model.

Table 15. Anti-Ship Missile Data (after Open Source Intelligence Project 2011, 70–75)

ASM AoA	#1	#2	#3	#4
	Noor-2	Kosar	Nasr	Harpoon
Speed (m/s)	306	290	306	272
Range (m)	120,000	25,000	35,000	124,000
Warhead (kg)	165	30	130	224
Guidance Data	Data Link for OTH Targets	TV or Active Radar	TV, Active Radar, or IIR	Active Radar

(2) UAV/UCAV Selection

A large amount of data was uncovered during the UAV/UCAV research, but only a few of the multiple UAV/UCAV platforms were selected for analysis. Table 16 contains data for the six platform types that were selected based on the CONOPS. UAV technologies are greatly advancing and UCAVs are becoming more capable of delivering large amounts of firepower against U.S. assets. Instead of rocket-propelled grenades, UCAVs are now able to carry ASMs, bombs and precision-guided munitions (Press TV 2013). After review of the data, the selected UAV type was the Yasir and the UCAV type was the Ababil-3. The Yasir is similar to America's ScanEagle so more open source data was available on this UAV threat type (Cenciotti 2013a). The UCAV Ababil-3 was the best candidate for selection due to its operational status and available open source data through IHS Jane's (Binnie 2014a).

Table 16. UAV/UCAV Data (see Appendix A)

UAV/UCAV AoA	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**
Name	Mohajer	Ababil-3	Ra'ad 85	Yasir	Karrar	Fotros
Speed (m/s)	53.6	55.5		41.2	264	
Range (m)	150000	100000	100000	200000	1000000	2000000
Max Altitude (m)	4572	5000		4572	12000	7620
Flight Time (hours)	7	4		8		30
Wingspan (m)	5.3	3.2		3.11	3	
Weapons		4 x AGM-114 Hellfires	Various		2 x 115 kg bombs	

(3) Small Boat Selection

Following the same process, the small boat threat data was determined for the model. As with the UAV/UCAV selection, there were multiple small boat threats (FAC/FIAC) to choose from. The options were narrowed down to six small boat classes and then each one was analyzed for model implementation. Based on the research in Table 17, the IPS-16 FAC provided the best data for the BOE model because this class of small boat represents a significant portion of the Iranian FAC forces, they are some of the fastest naval vessels in the Persian Gulf, and there is a current production line of new variants such as the Zofahar that are being built (FAS 2009, 14).

Table 17. Small Boat Data (after Open Source Intelligence Project 2011, 32, 34–36, 40)

Small Boat AoA	**#1**	**#2**	**#3**	**#5**	**#6**
Name	Kaman/SINA Class	Thondor Class	C-14 “China Cat” Class	Kajami Class	IPS-16 Peykaap-II Missile Class
Speed (m/s)	19.3	18	25.7	20.6	26.7
Weapons	4xASM 2xGuns	4xASM 4xGuns	4xASM 1xMLRS 1xGun 1xMachine Gun	2xTorpedo Tubes	4xASMs 2xMachine Guns 2xTorpedo Tubes

(4) Assumptions

Some of the data was completed using engineering assumptions based on open source data. The following Target Assumptions were made based on open source research and Excel model limitations:

- UAVs/UCAVs are considered suicide drones
- All threats are launched at the same time
- ASMs near the terminal phase will be used for threat engagement

Based on the available open source data for threat attributes and engineering assumptions, a table was assembled to organize the remaining threat data for input to the model (Table 18).

Table 18. Attributes of Selected Threat Types (after Microwaves101 2015; Open Source Intelligence Project 2011)

Threat Type	**RCS (m^2)**	**Attack Height (m)**
Missile	0.5	5
UAV	1	4572
UCAV	1	500
Small Boat	10	1.93

The attack height values were developed from different sources. The source of the five-meter attack height for the missile threat was the write up on the C-802 missile by Federation of American Scientists (FAS 2000). The attack height for the UAV was based on known height limit of conventional anti-aircraft fire, which is typically 15,000 feet (4572 meters), and its role as a reconnaissance platform. The attack height for the UCAV was derived from a potential missile type that could be employed on the UCAV platform. This missile employed by UCAVs would be similar to a Hellfire type missile. The proposed attack height for an UCAV using lock on before launch mode would be roughly 1,500 feet (457 meters) this was rounded to 500 meters for the model (GlobalSecurity.org 2011i). The boat attack height was determined by the overall height above the waterline for the vessel of the IPS-16 FAC (Open Source Intelligence Project 2011).

(5) Final Threat Data Selection

The final threat information relevant for this analysis is shown in Table 19.

Table 19. Threat Data

Threat	Threat Number	P(HEL intercept)	P(CIWS intercept)	Threat Speed (m/s)	Threat RCS (m^2)	Threat Height (m)	Threat Width (m)	Attack Height (m)
Missile	1	0.4	0.3	306	0.5	0.36	0.36	5
UAV	2	0.7	0.6	41	1	0.3	3.11	4572
UCAV	3	0.65	0.5	55.5	1	0.5	5.8	500
Boat	4	0.9	0.7	26.7	10	1.93	3.75	1.93

b. Ship Countermeasures AoA for BOE Model

Selecting the weapon systems on the ship to counter the threats also required engineering analysis due to the number of weapon options available. The determination came down to the project schedule and the amount of effort required to code the HEL and other selected effectors in the model. The HEL being a complex system to code in the model actually forced the systems engineering team to consider only one or two more additional effectors. To coincide with the Navy’s Defense in Depth concept, a missile system and a short-range gun system were the likely choices to supplement a HEL. The options were narrowed down to the ESSM and CIWS due to the self-defense aspect of the combat system. Both of these effectors were coded in the BOE model with the HEL but only the CIWS was coded with the HEL in the ExtendSim model due to higher complexity in the ExtendSim code. In this way, the models reflected the Navy's Defense in Depth concept.

The CIWS has a max range of 2,000 yards, holds 1550 rounds and fires at rate of 3000–4500 rounds per minute (Pike 2003). For the purposes of the model, the variable input was the number of salvos per CIWS. This value was set to seven with an assumption that one salvo equaled about 200 rounds.

(1) CIWS and BDA

While BDA may increase the live fire effectiveness of lasers in an engagement scenario, there may be zero advantage for other kinetic systems. The Phalanx CIWS is a six-barrel Gatling Cannon that expends 20 mm armor piercing tungsten rounds at a rate of 3000 to 4500 rounds per minute and a max range of approximately one nautical mile (Pike 2003). The model assumes that the CIWS typically fires 200-round bursts in order to allow time for system assessment and to avoid depleting the magazine too quickly. With an effective range of 3.6 km and muzzle velocity of 1,100 m/s, the CIWS system cannot incorporate the new BDA system to manage and conserve ammunition. This is because by the time the first round reaches the target, the last round has already been fired. The timeline associated with a CIWS threat engagement are shown in the equations below. These equations assume no drag effects.

- Time for First Round to Reach Target:

$$t_{Round\ to\ Target} = \frac{Max\ Effective\ Range}{Muzzle\ Velocity} = \frac{3600m}{1100m/s} = 3.27s$$

- Time to fire all rounds for engagement:

$$t_{Fire\ 1\ Salvo} = \frac{Salvo\ Size}{Rate\ of\ Fire} = \frac{200\ rounds}{75\ rounds/s} = 2.66s$$

- Time between last round being fired and potential impact of first round:

$$t_{Difference} = t_{Round\ to\ Target} - t_{Fire\ 1\ Salvo} = 3.27s - 2.66s = 0.61s$$

The 0.61-second time of flight is not enough time to provide input to the CIWS for any type of threat engagement efficiency. This is not to say that such a system could not exist for the CIWS but it is not a weapon system that is designed for efficiency as it is a ship's weapon of last resort. It is meant to expend as many rounds as possible as quickly as possible. With this in mind, the BDA system was not implemented on the CIWS but only the HEL for analysis.

(2) Modeling the HEL

HEL propagation is greatly affected by many different parameters, including, but not limited to: output power, wavelength aperture diameter, range to the target, the diffraction and jitter of the beam and the atmosphere. The maritime environment has high levels of humidity and other molecular matter that scatters and attenuates the laser energy. Thermal blooming and atmospheric turbulence may also limit the lethal fluence delivered to the target (McAulay 2011, A–B). While atmospheric effects are important, they were assumed to have no influence on the propagation for this model. An additional assumption was that the time to slew the HEL between targets would be ignored. The BOE model incorporated the HEL by using the equations for lethal fluence and atmospheric diffraction, an EO/IR sensor for the wide/narrow field of view sensor using Johnson's Criteria for target detection and recognition, and the Falling Body Equation to determine the time between mission kill and hard kill where the target hits the water. An EO/IR sensor is a critical component in the Acquisition, Tracking and Pointing (ATP) chain for the engagement of a threat with a directed energy weapon. It provides the fine level of tracking necessary to keep the beam spot on a specific portion of the target allowing the lethal level of fluence to accumulate. Stakeholders and advisors supported this method of modeling for the HEL.

Figure 30 below depicts the flow of the HEL portion of the model. The first step is to determine the distance to acquire (or detect) and track (or recognize) the threat. Once the threat has been recognized it can be engaged with the HEL if it is still in the engage window. If the threat is in the window, then the lase time is checked against the time available before the threat is inside the minimum engage distance. The threat is then lased and, if BDA is enabled, checked for kinematic change indicating mission kill. If nonthreating kinematic change the engagement is complete. If kinematic change is not detected the HEL continues to engage until the threat reaches the surface of the ocean. Once the engagement is finished the HEL enters the cool down phase. The result of the lase time and cool down time are totaled as the cycle time for the engagement. The cycle time is then used to determine if the HEL can engage the next target before it is closer then and minimum engage distance. In this case the threat will be engaged by the CIWS.

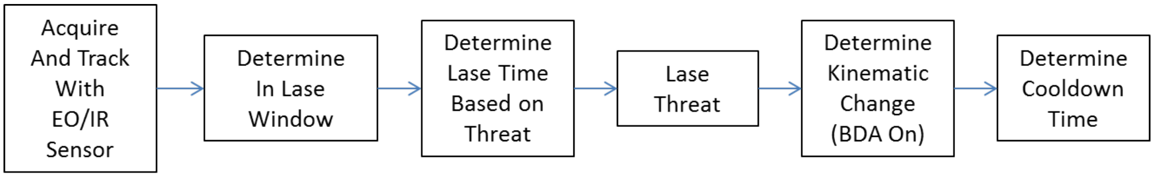


Figure 30. HEL Portion of BOE Model

The HEL parameters used for the model are shown below in Table 20. The model assumes that Linear Sigma (Jitter) equals Sigma (Diffraction); therefore, Sigma (Diffraction) = 2.53E-02 meters and Linear Sigma (Jitter) = 2.53E-02 meters. The equations below were used to calculate the values used in the model (Merritt 2012, 11)

Table 20. HEL Properties

Height	8 meters
Aperture Size	0.12 meters
Wavelength	1.06 x 10^{-6} meters
Maximum Range	10,000 meters
Minimum Range	250 meters
Power	100 kW
Sigma (Diffraction)	2.53 x 10^{-2} meters
Linear Sigma (Jitter)	2.53 x 10^{-2} meters
Angular Sigma (Jitter)	4.11 x 10^{-6} rad

- Sigma Diffraction (σ_D)

$$\sigma_D = 2^{1/2} R\lambda/\pi D$$

Where:
R = *Range (meters)*
λ = *Wavelength (meters)*
D = *aperture diameter (meters)*

- Linear Sigma Jitter (σ_J) -meters

$$\sigma_J = 2 \ x \ \sigma_D$$
$$\text{Where:}$$
$$\sigma_D = \text{Sigma Diffraction (meters)}$$

- Angular Sigma Jitter (σ_J) - radians

$$\sigma_J^2 \ (rad) = \sigma_J^2 \ (meters) \, / \, R^2$$
$$\text{Where:}$$
$$\sigma_J \ (meters) = \text{Linear Sigma Jitter}$$
$$R = \text{Range (meters)}$$

- Beam Radius

$$rad = R\lambda / D$$
$$\text{Where:}$$
$$R = \text{Range (meters)}$$
$$\lambda = \text{Wavelength (meters)}$$
$$D = \text{Aperture Diameter (meters)}$$

The Angular Sigma (Jitter) = 4.11E-06 rad. Figure 31 below depicts the beam radius at the target versus range.

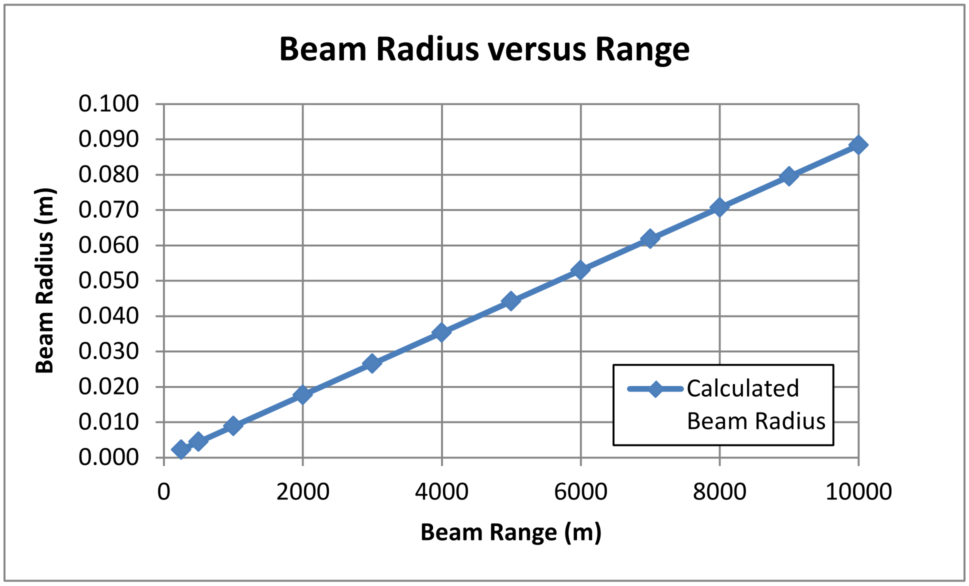


Figure 31. Beam Radius versus Range

The effect of jitter and diffraction can be seen in Figure 32. This graph compares the beam profile of the unjittered beam from the model with the same beam with the effects of both jitter and diffraction.

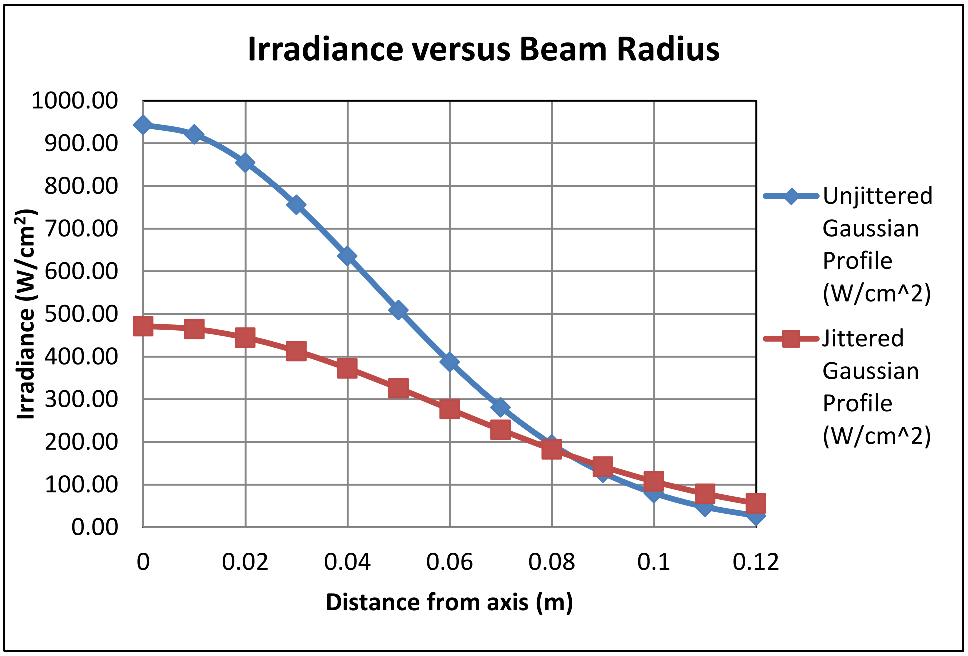


Figure 32. Effects of Jitter on Beam Irradiance

The effect of the ratio between Linear Sigma (Jitter) and Sigma (Diffraction) was further investigated. The ratio of Linear Sigma (Jitter) increase in relation to Sigma (Diffraction) the Angular Sigma (Jitter) increased as a direct result. This increase resulted in a decrease of the irradiance on the threat that in turn increased the dwell time on the threat to build up the lethal fluence. Scenario 1 with BDA off was simulated with Linear Sigma (Jitter) equal to 1x, 2x, and 10x Sigma (Diffraction). The combat system neutralized fewer threats in a fixed amount of time, depicted in Table 21 below. Reducing the HEL systems jitter is a requirement for them to be used as an effective weapon.

Table 21. Effects of Increased Jitter

Linear Sigma (Jitter)	Angular Sigma (Jitter)	I_{PJ}	Kills
1x σ_D	4.11E-2 m	471.7 (W/cm^2)	19
2x	8.21E-2 m	188.7 (W/cm^2)	17
10x	4.11E-1 m	9.34 (W/cm^2)	6

The HEL aperture size = 0.12 m. Furthermore, the HEL Max Range is set to 10,000 meters and the Min Range = 250 m. The HEL operates on 100 kW of power and the quantity of HEL weapons is entered as either a one or a two (Campos et al. 2011).

The properties of the notional ship's sensors are shown in Table 22. In order to determine when the EO/IR sensor would be able to detect and track each target type a method using Johnson's Criteria was used. John Johnson developed these criteria in the 1950s (Harney 2013a, 426). Based on a series of experiments on perception he was able to determine the number of resels required for different levels of image quality of a target (Harney 2013a, 426). The term "resel" is a contraction of the words "resolution element" (Harney 2013a, 417). The number of resels required varies based on the level of image quality that is necessary. For the purpose of this model the two image quality levels that we selected were detection and recognition. "Detection" indicates that the EO/IR sensor can see something but it is unable to provide the detailed image required for accurate beam placement. "Recognition" indicates that the threat image is sufficient that the HEL can target a specific section where the accumulation of fluence would create damage. The new values for Johnson's Criteria for Detection set the number of resels at 1.5 and Recognition at 6.0 resels. The EO/IR wavelength (TV) = 8E-7 meters and its diameter is 0.1 meters. The HEL wavelength = 1.06E-6 meters. The maximum range of 20,000 meters was assumed from Harney (Harney 2013a, 430).

Table 22. Sensor Properties

	EO/IR	SPQ-9B
Height	8 m	25 m
Aperture Size	0.1 m	n/a
Range	20,000 m (max)	36,576 m (nominal)
Wavelength	8×10^{-7} m	n/a
Detection	1.5 resel	n/a
Recognition	6.0 resel	n/a

Current weapon engagement methodology destroys the target "before they impact their intended target," which is termed a "hard kill" system (Meyer 1998, 7). In a maritime environment, this means that the threat will be engaged until it makes contact with the surface of the ocean. The Falling Body Equation was implemented into the BOE based on input from Raytheon stakeholders to determine the time from mission kill to the target impact to the water. The maximum engage, or dwell, time required to achieve a hard kill is the HEL lethal fluence lase time plus the time for the threat to crash from Attack Height (sec) or HEL lethal fluence Lase Time plus the Falling Body Equation.

- Time to complete hard kill ($t_{Max\ Engage}$):

$$t_{Max\ Engage} = T_D + T_{Freefall}$$

- HEL lethal fluence Lase Time (T_D):

$$T_D = F_D / I$$

(Perram, 2010, p. 325)

Where:

F_D = *Lethal Fluence*

I = *Delivered Irradiance*

- HEL lethal fluence (F_D):

$$F_D = \rho l(C(T_M - T_0) + H_m) / (1 - R)$$

(Perram 2010, 332)

Where:

ρ =*Density* (g/cm^3)

l = *Target thickness (cm)*

C = *Specific heat (J/g-K)*

T_M =*Melting temperature (K)*

T_0 =*Initial temperature (K)*

H_m = *Latent heat*

R = *surface reflectivity*

- Delivered Irradiance (I):

$$I = P / A$$

(Perram, 2010, p. 325)

Where:

P = *Laser power (watts)*

A = *Beam area* (cm^2)

- Time for target to hit the water ($T_{Freefall}$):

$$T_{Freefall} = ((2*h) / g)^{0.5}$$

Where:

h = *height of target (m)*

g = *acceleration due to gravity* (m/s^2)

This provides the maximum time the HEL must dwell on the target before entering the cooldown phase of the cycle. The current cooldown time is 1.5 times the duration of the lase time.

A time input was installed in the model to make the scenario realistic and to provide another analysis approach since one of the features was to reduce the amount of HEL dwell time to the minimum required for a mission kill, thereby reducing the overall cycle time per target. Data assumptions for the SPQ-9B time to detect and the time to acquire the target calculations were made with help from project advisor Professor Green during a meeting held December 9, 2014. Data assumptions for the EO/IR sensor were developed from Harney's Combat Systems Engineering (Harney 2013a, 426–432).

The engagement scenario consisted of 50 randomized threats. These threats were prioritized based on the range to ownship and attack speed as the Threat Priority. This value was used to sort the threats for engagement. An output of the number of kills per weapon and threat types killed per run provided a method to measure system performance change when BDA was activated. The time data could also be evaluated to determine the lase time and cycle time effects with BDA On.

D. EXTENDSIM MODEL

In parallel with the BOE model design, an ExtendSim model was developed as the higher order systems model. The M&S in ExtendSim leveraged an existing model from the 2011 HEL Capstone Project because a model evaluation predicted a high reuse opportunity that would maximize the code design schedule. The model inputs were coded using data from the BOE model, which included the threat data received from the combat system. Attribute values for P_k, minimum and maximum engage ranges, and threat data were set in the input section. This input data was used in the combat system (threat prioritization, dwell time, P_k, weapon scheduling) section of the model, as well as the CIWS and HEL section of the model. The threat inputs were randomized for a realistic scenario. The threats were assigned to either a CIWS or HEL based on threat prioritization, dwell time calculation and the P_k for the weapon-threat pair. The threats entered a queue for a CIWS or HEL based on the weapon scheduling for engagement. The HEL and CIWS performed a check of each threat in their queues based on their set engage ranges and then engaged the threat if the threat was within their range. The HEL was limited by a cycle time calculated as dwell time plus cool down time. The CIWS was assumed to contain seven salvos just like the BOE model and used a “shoot-look-shoot” cycle time method. Both the CIWS and HEL determined the number of successful engagements and the number of missed targets and this data was provided back to the combat system section to improve the dwell time required for threat mission kills. The final integrated ExtendSim model is located in Appendix B.

E. SUMMARY

A detailed BOE Model was developed in Excel as part of the mathematical M&S methodology. This model was built and coded with open source data, engineering assumptions, class materials, and equations from *Introduction to Laser Weapon Systems* (Perram, et al. 2010, 324, 332), Combat Systems Engineering, Vol. 1 (Harney 2013a, 112–113), and Radar Basics (Wolff 2014) with support from project advisors and Raytheon stakeholders. This model provided the data required to determine if the BDA system provided an increase in the number of HEL kills.

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V. MODELING AND SIMULATION ANALYSIS

A. INTRODUCTION

The next step in Vitech’s Top Down MBSE Process diagram is step 10 “Perform Effectiveness and Feasibility Analysis.” This included the development of test scenarios and data output functions for systems analysis. These simulations would provide output data for analysis, specifically system performance with BDA Off versus system performance with BDA On. This performance was translated into picture form to communicate the performance deltas. An Engagement Time Sequence and a Layered Defense Graphic provided a summary of the performance improvement for a BDA system on the HEL Combat System.

B. SIMULATIONS

Four scenarios were identified and selected for the system analysis event using the BOE model Table 23. Missiles are set to zero based on the information described in Chapter IV for weapon selection.

Table 23. BOE Model Simulations for BDA System Analysis

Scenario #	**Threat Types**			**Weapon and quantity**		
		Threat Quantity	**BDA On/Off**	**ESSM**	**HEL**	**CIWS**
1	All	50	Off	0	1	1
	All	50	On	0	1	1
2	UAV, UCAV, Boat	50	Off	0	1	1
	UAV, UCAV, Boat	50	On	0	1	1
3	All	50	Off	0	2	2
	All	50	On	0	2	2
4	UAV, UCAV, Boat	50	Off	0	2	2
	UAV, UCAV, Boat	50	On	0	2	2

C. BOE SIMULATION RESULTS AND CONCLUSIONS

The BOE results are provided in a summary sheet at the end of Chapter V with the final BOE model embedded in Appendix D. With BDA On, the results of simulation scenarios 1–4 show a noticeable increase in the P_k for the total threat engagement and a quite significant increase in the HEL's P_k.

1. HEL Engagement Time Sequence

An engagement time sequence chart provides another method for the BDA system analysis. Figure 33 is the sequence with BDA Off and Figure 34 is the sequence with BDA On. The value of a BDA system for the HEL engagement is shown on the back end of the time sequence where the "Engage with HEL" time decreases for all four threat types.

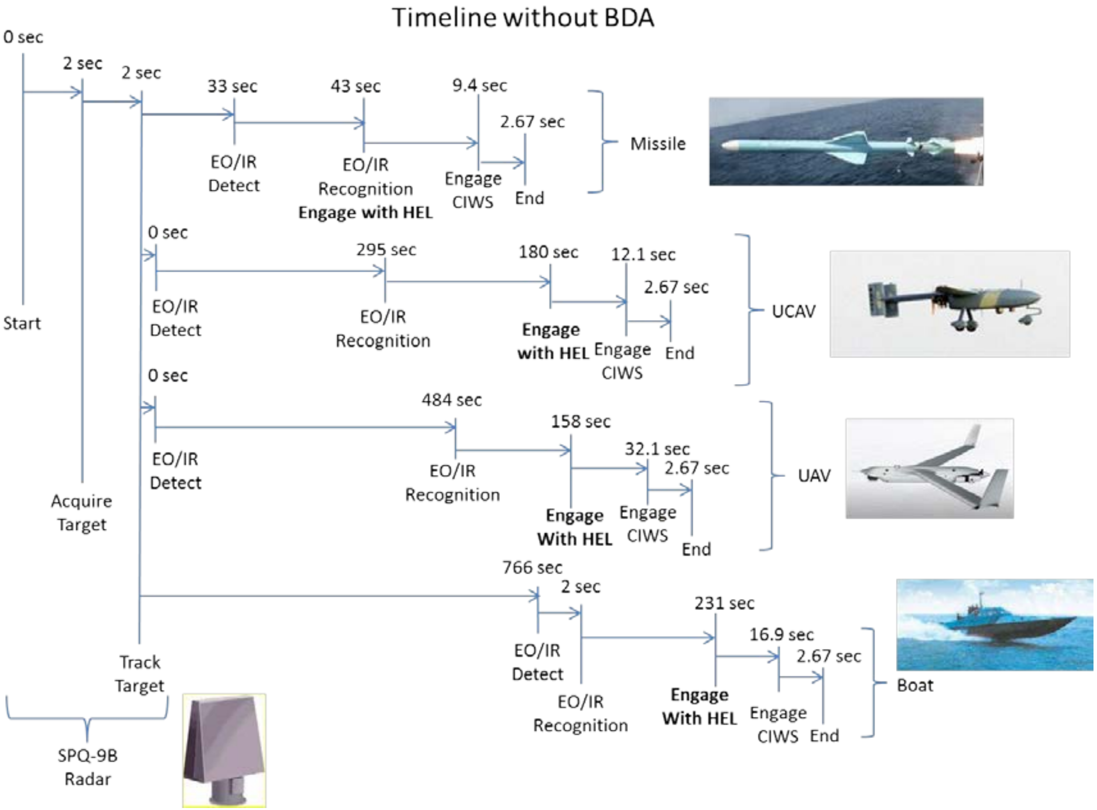

Figure 33. Engagement Time Sequence – BDA Off

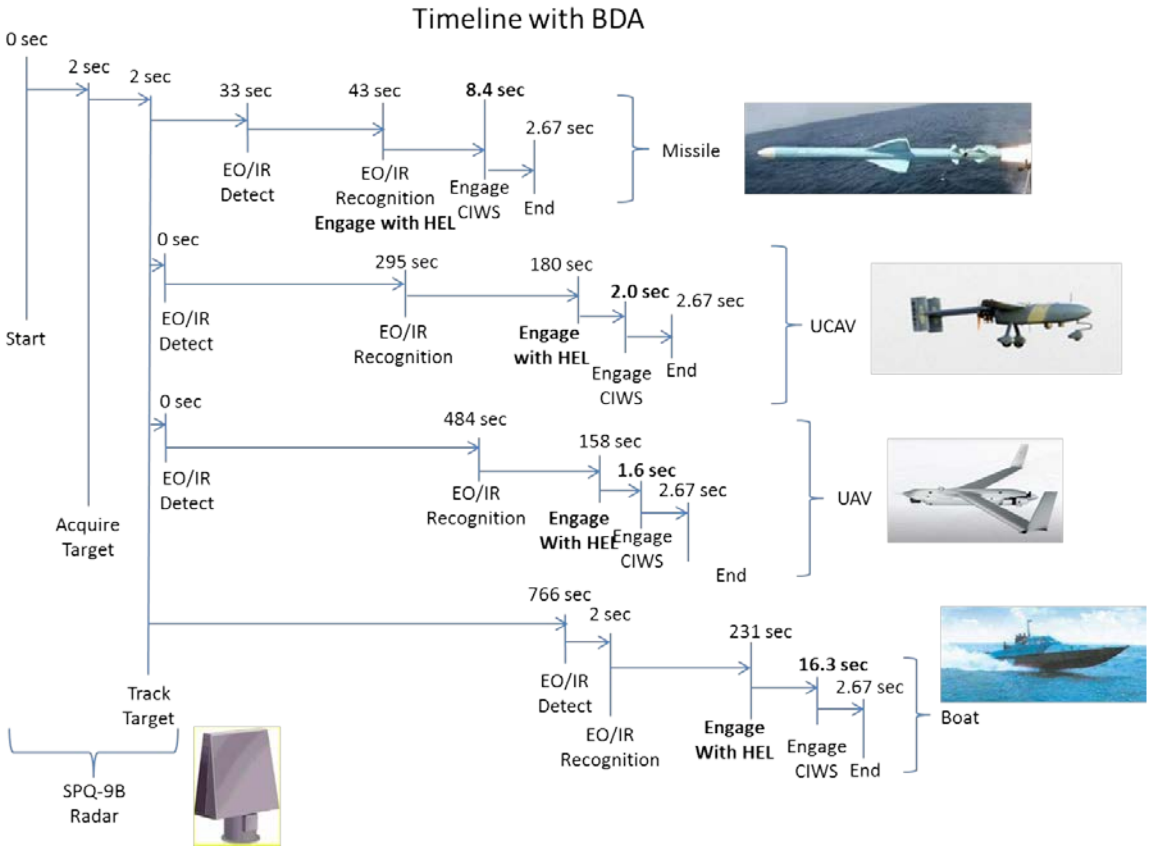

Figure 34. Engagement Sequence – BDA On

Without BDA (baseline design), the HEL engages the UAV for 32.2 seconds, whereas BDA On shows the HEL engaging the UAV for 1.6 seconds to complete a mission kill. The HEL engagement with BDA reduces to about one twentieth of the baseline engagement time. This data, shown in Table 24, demonstrates a far more efficient dwell time with BDA On, allowing for more threat engagements overall for the combat system.

Table 24. HEL Engage Time - BDA Off versus BDA On

Threat Type	HEL Engage Time (sec) BDA Off	HEL Engage Time (sec) BDA On	% Improvement
Missile	9.4	8.4	11%
UCAV	12.1	2.0	83%
UAV	32.1	1.6	95%
Boat	16.9	16.3	4%

2. HEL in the Shipboard Layered Defense

Current Navy strategy uses a layered defense model to manage threat engagements. Figure 10 shows the layered defense concept in terms of sensor and weapon capability ranges in the BOE model. The SPQ-9B has a nominal range of 36 km to provide early threat detection. The EO/IR sensor tracks the targets detected by the SPQ-9B at a maximum of 20 km for Recognition processing per Johnson's Criteria, which allows the target to be engaged by the HEL. Next, the weapon systems from mid-range (HEL) to short-range (CIWS) provide the final two layers around the LPD for ship self-defense.

Similarly, the HEL engagement of the four different threat types in the simulation provided another layered defense concept of the HEL's threat engagement process. Using the BOE model for the range and height data, this chart provides an excellent snapshot of the beginning of the HEL engagement process as shown in Figure 11.

The missile threat is the closest threat at the start of the threat scenario followed by the UAV/UCAV and finally the small boat threats. The combined BOE simulation data for Threat Scenarios 1–4 provided encouraging data that the BDA system concept definitely adds significant value to the HEL Combat System and is worthy of further R&D.

3. BDA Kill Efficiency Threshold

A HEL BDA working group meeting discussed the threshold to measure kill efficiency for the BDA system. It was decided that a kill efficiency increase above 25% would warrant further study.

4. Conclusions from the BOE Threat Scenarios

A 25% increase in threat engagements was a realistic expectation. However, as shown in Table 25, the actual increase in HEL Combat System performance exceeded that expectation by more than double in one simulation. Scenarios 1 through 4 were run with and without BDA to determine whether was a performance improvement. On average, the BDA system provided an average increase of 33% in the HEL system kills across all four test scenarios and a 21% increase in overall combat system kills.

Table 25. BDA Kill Results

Scenario (1000 runs each)	HEL	CIWS	BDA	Threat Type	HEL Kill Improvement with BDA (%)	Overall Kill improvement with BDA (%)
1	1	1	Off	All	37	29
	1	1	On	All		
2	1	1	Off	UAV, UCAV, Boat	37	34
	1	1	On	UAV, UCAV, Boat		
3	2	2	Off	All	32	17
	2	2	On	All		
4	2	2	Off	UAV, UCAV, Boat	26	4
	2	2	On	UAV, UCAV, Boat		
Average Improvement					**33**	**21**

Note the low improvement in scenario 4 for overall kills. This is a result of setting 50 as the maximum number of threats. In this case, the combination of two HELs and two CIWS averaged 49.73 kills over 1000 runs. The median value of overall threats killed was 50; therefore, the entire raid was annihilated over 50% of the time in this configuration.

D. SUMMARY

The BOE results exceeded the threshold for the increase in the number of kills for a HEL Combat System against swarm threat scenarios. The threshold was 25% and the kill improvement for the HEL ranged between 26% and 37%. The BOE results favor the development of a BDA system, but this promising data only scratches the surface of proving the concept is worthy of development. Further analysis with more detailed threat scenarios, real data in place of assumed data and a more detailed model is necessary to provide a real-world assessment of the operational BDA concept. After a more refined technical proof of concept, many technical risks will still have to be discussed and addressed in order to answer the question of “how do we do BDA?” in an end-to-end system concept. This new study supports a new definition of kill assessment and survivability for a HEL Combat System. It will also shape the set of requirements for the new BDA system on a HEL Combat System.

VI. SYSTEM INTEGRATION

A. INTRODUCTION

As part of the systems feasibility analysis in Step 10 of Vitech's Top Down MBSE Process, another technical analysis was performed in order to integrate the three key nodes of the model and to determine the combat system integration approach for the HEL and BDA systems. The act of combining two or more elements into a whole system is systems integration. The elements can be hardware, software or a combination of both. In the case of the M&S integration, the three key nodes are software based. Hardware and Software systems have to be integrated into the ship system and combat system for HEL and BDA integration.

B. METHODOLOGY FOR INTEGRATION

The integration method used was a bottom-up Integration as shown in Figure 35 (Muehlbach 2014c, 32). As depicted, the M&S modules are grouped together into builds and then integrated. For the M&S in ExtendSim, each key node contained sub-modules that were grouped into complete builds. Each key node was integrated into the overall ExtendSim model for debugging, which describes a bottom-up integration. This methodology also included integration requirements development and System Interface Descriptions (SV-1).

C. SYSTEM ARCHITECTURE DIAGRAMS

Based on the interface requirements established in Chapter III, a SV-1 was developed for both the ExtendSim Model integration and the BDA system integration. The SV-1 is the system interface description made up of system nodes, interfaces and system functions (Dam 2006, 54).

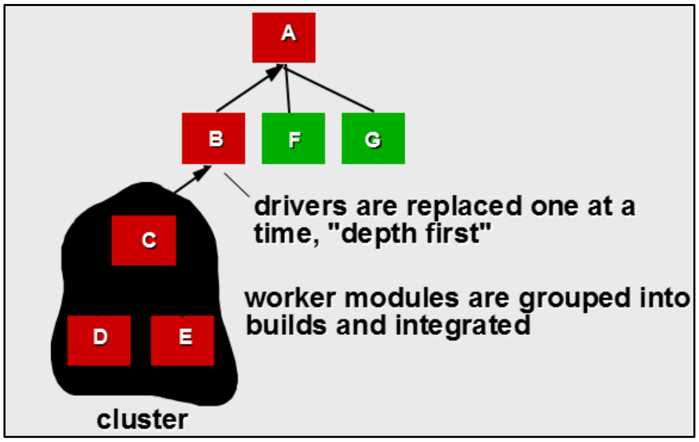

Figure 35. Bottom-Up Integration Method (from Muehlbach 2014c)

1. ExtendSim Model SV-1

Figure 36 depicts the SV-1 diagram for the ExtendSim Model. The four nodes are the Threat Node, Mission System Node, Threat Engagement Node and the Mission Analysis Node.

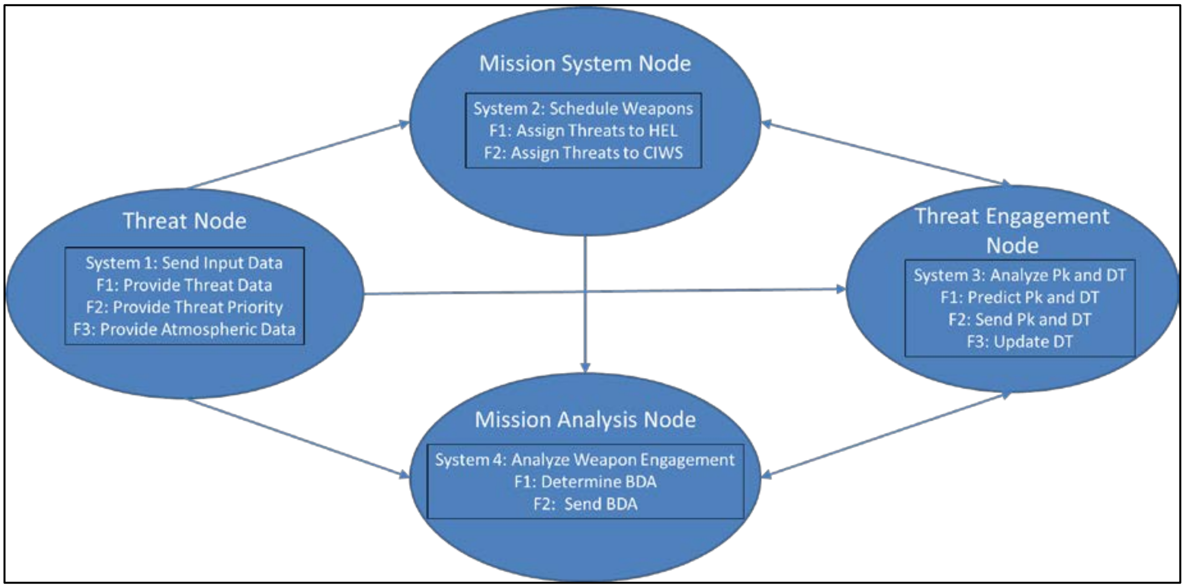

Figure 36. SV-1 Diagram for ExtendSim Model

The Threat Node provides data from the ship and combat system to the Mission System Node, Threat Engagement Node and Mission Analysis Node that require this information for their operational functions. The three functions include:

1. F1: Provide Threat Data
2. F2: Provide Threat Priority
3. F3: Provide Atmospheric Data

The Mission System Node receives inputs from the Threat Node and the Threat Engagement Node in order to Schedule Weapons. The predicted P_k and dwell time and the updated dwell time support the weapon schedule function for optimal ship survivability. This node includes the following two functions:

1. F1: Assign Threats to HEL
2. F2: Assign Threats to CIWS

The Threat Engagement Node analyzes P_k and dwell time using data from the Threat Node, Mission System Node and Mission Analysis Node. With this data, it performs the following three functions:

1. F1: Predict P_k and Dwell Time
2. F2: Send P_k and Dwell Time
3. F3: Update Dwell Time

The dwell time update is performed when the BDA data is determined and provided to the Threat Engagement Node for dwell time adjustment. For instance, if a dwell time prediction called for a ten second dwell time for a hard kill and the BDA provided a mission kill dwell time of two seconds, then the HEL dwell time for that threat type would update to two seconds. BDA performs this function by calculating a mission kill dwell time for the weapon-threat pair based on threat kinematic data and then providing this new dwell time to the combat system for its calculation of dwell time for new weapon-threat pairs. Per the diagram, the new dwell time is sent to the Mission System Node to provide an improved weapon scheduling function, which is performed by the combat system. The Mission Analysis Node and Threat Engagement Node interface is imperative for combat system efficiency.

Finally, the Mission Analysis Node, which accepts inputs from the Threat Node, Mission System Node and Threat Engagement Node performs the following functions:

1. F1: Determine BDA
2. F2: Send BDA

This SV-1 diagram provided a helpful guide to integrate the four key nodes in the ExtendSim Model.

2. HEL and BDA/Dwell Time SV-1

A separate analysis was performed to determine an integration approach for the HEL and BDA/Dwell Time systems on a surface ship. A SV-1 was developed for the HEL, BDA and Dwell Time system integration. The SV-1 in Figure 37 provides the system interface description with associated system nodes, interfaces and functions.

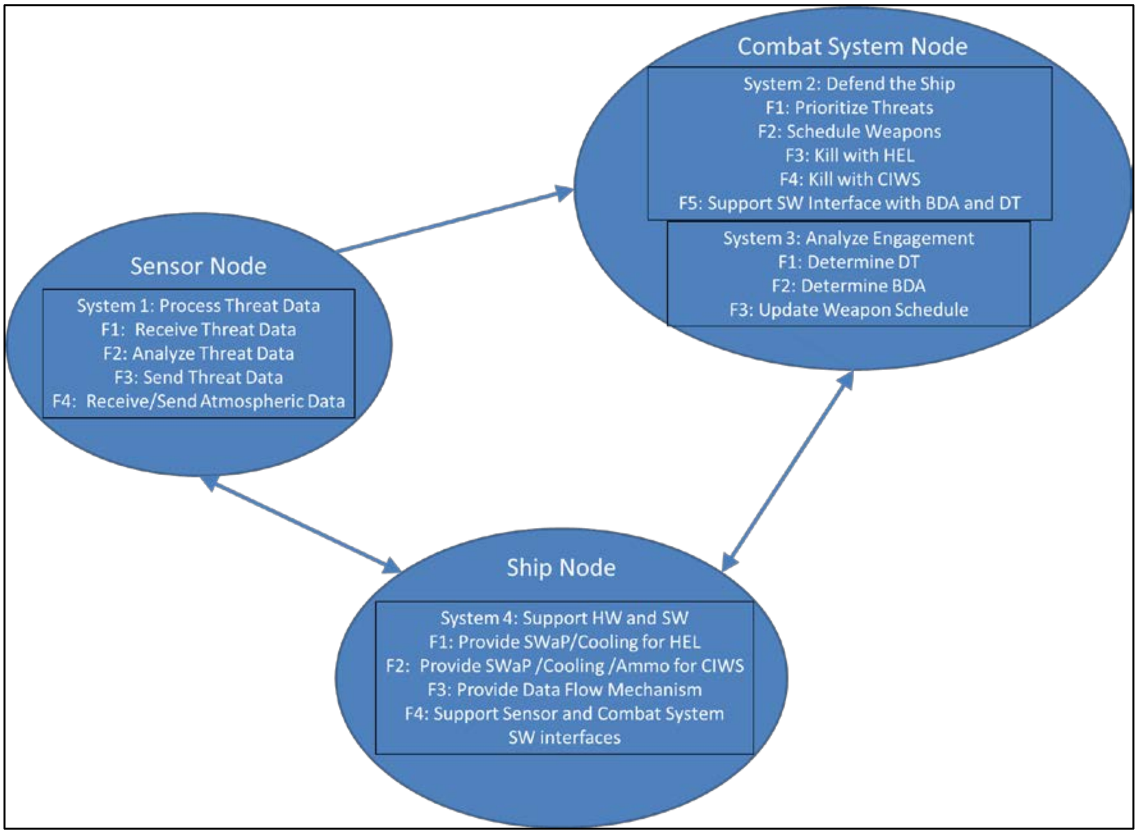

Figure 37. SV-1 for HEL and BDA/Dwell Time

The three key nodes identified are the Sensor Node, Combat System Node and the Ship Node. This SV-1 was a simplified approach to determine how to integrate the HEL, BDA and Dwell Time systems in the context of the ship type, combat system functions and sensor data.

The Sensor Node processes the threat, navigation and atmospheric data for input to the Combat System so that the combat system can defend the ship. This node would include sensors such as radars, EO/IR sensors, navigation sensors and atmospheric sensors. The Ship Node would provide hardware and software locations to support this node function. The Sensor Node provides the following functions:

1. F1: Receive Threat Data
2. F2: Analyze Threat Data
3. F3: Send Threat Data
4. F4: Receive/Send Navigation Data
5. F5: Receive/Send Atmospheric Data

The Combat System Node includes two main systems: Defend the Ship and Analyze the Engagement. This node receives input data from the sensors, receives hardware and software support from the ship and provides the defense capability to the ship. The following functions are included in defending the ship:

1. F1: Prioritize Threats
2. F2: Schedule Weapons
3. F3: Kill with HEL
4. F4: Kill with CIWS
5. F5: Support SW interface with BDA and Dwell Time

The following functions fall under the engagement analysis by the combat system, which will greatly improve the survivability of the ship:

1. F1: Determine Dwell Time
2. F2: Determine BDA
3. F3: Update Weapon Schedule

This SV-1 diagram provided a great basis for methods to integrate the HEL, BDA and Dwell Time SoS on an existing ship platform. An AoA of HELs and ship platforms was performed in order to investigate possible hardware and software for combat systems and ship integration.

D. HEL INTEGRATION ON A SHIP

Because of the Low TRL level/high risk status of directed energy weapons, there were a few candidates worth considering for installation on a Navy ship platform. The trade study in Appendix C analyzed a FEL versus a LaWS for integration and also ship type for installation. Although the FEL program was cancelled, it is still a likely candidate for consideration for a future installation on a ship. The analysis included information available through open source data references. The evaluation criteria included beam power, BQ, power required, power efficiency, TRL, and system test status. The FEL is a TRL level four (ONR 2008). Due to the low technology readiness level, low system test status, and power requirement for the FEL (ONR 2008), the LaWS turned out to be the clear winner for integration on a ship based on its performance, size and power requirement (O'Rourke 2014, XX). The LaWS can counter UAVs, Electro-optical (EO) sensors and EO-guided missiles. Its beam power is achieved by incoherently combining six fiber laser beamlets, which means the beams are out of phase of each other (Fan 2005, XX). Because of the successful testing onboard the USS Ponce, it is anticipated that the TRL for LaWS is a six (O'Rourke 2014, XX).

The ship types available for the LaWS integration are plentiful. The options for analysis included the DDG-1000, Arleigh Burke Destroyer and LPD. Based on the evaluation in Table 26 the LaWS can be integrated on each ship types based on the available open source data for all types. It appears that the FEL would only be an option for the DDG 1000 and the LPD due to the large 10 MW power requirement.

Table 26. Analysis of Three Alternative Ship Platforms for HEL Integration AoA (after U.S. Navy 2014a; U.S. Navy 2014c)

PLATFORM	DDG 1000	DDG-51	LPD
Installed Power	78 MW	3 x 2500 kW	5 x 2500 kW
Weight	14500 tons	8000-10000 Tons	25,000 tons
Ship Length	600 ft	505 ft	684 ft
Beam	80.7 ft	66 ft	105
Cost ($B)	3.45	1.843	1.7

E. DWELL TIME AND BDA SYSTEM INTEGRATION

With regard to the Dwell Time and BDA systems, the concept of software integration of new code into an existing combat system code is certainly feasible, though not without technical risk. New sensors and effectors are brought forth for integration on existing combat systems for both new and existing ship platforms. A great combat system for this approach is an open architecture (OA) system such as the SSDS, which “serves as the integrator for the individual detection and engagement elements of the ships’ combat system” (Rudderow 2002). The technical risk comes from the following based on engineering experience:

1. Older coding languages
2. Varying data message formats
3. Differing types of algorithms and interfaces
4. Limited testing resources
5. Information Assurance requirements (new doctrine)

Each of these risks have to be considered when integrating the new Dwell Time and BDA software into an existing combat system. These risks also translate into increased Non-Recurring Engineering (NRE) cost for DOD acquisition offices.

F. SUMMARY

Integrating the BDA function onto existing HEL Combat Systems appears likely due to the increased efficiency and power management capabilities it provides during operational scenarios. More engineering analysis is required to design the BDA system with integration in mind. A usability assessment and an analysis of the HEL Combat System software and hardware interfaces would provide critical input to the BDA system integration approach.

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VII. CONCLUSION

A. SYSTEMS ENGINEERING THE HEL BDA CONCEPT

The systems engineering process from start to finish provided invaluable data to support a new BDA capability for an HEL on a ship combat system. With limited resources such as time, personnel availability, M&S coding experience and combat system knowledge, this systems engineering project was a true test of commitment to a proof of concept for further R&D of the BDA system. The project had to show value to warships with an HEL through battle space optimization. The concept had to provide increased survivability of the ship and her crew by an increased number of kills.

B. ANSWERS TO THE RESEARCH QUESTIONS

The following research questions were generated for the HEL BDA Capstone Project:

1. Based on threat scenarios in the model and simulation, against what type(s) of threats will the HEL Combat System be the most effective?

The four types of threats in the model and simulation scenarios were UAVs, UCAVs, FAC and ASCMs. Based on the 1000 runs of 50 randomized threats in the BOE model, the HEL Combat System is the most effective at engaging UAV threats and is least effective engaging ASCM threats.

Figure 38 is the HEL-UAV Engagement Time Sequence with and without BDA. The engagement time for a UAV without BDA is 32.1 seconds. The engagement time with BDA for a mission kill engagement analysis turned out to be only 1.6 seconds. Saving 30.5 seconds of engagement time means that the HEL completes the cooldown phase much sooner and is ready to engage another threat after only 2.4 seconds of cooldown.

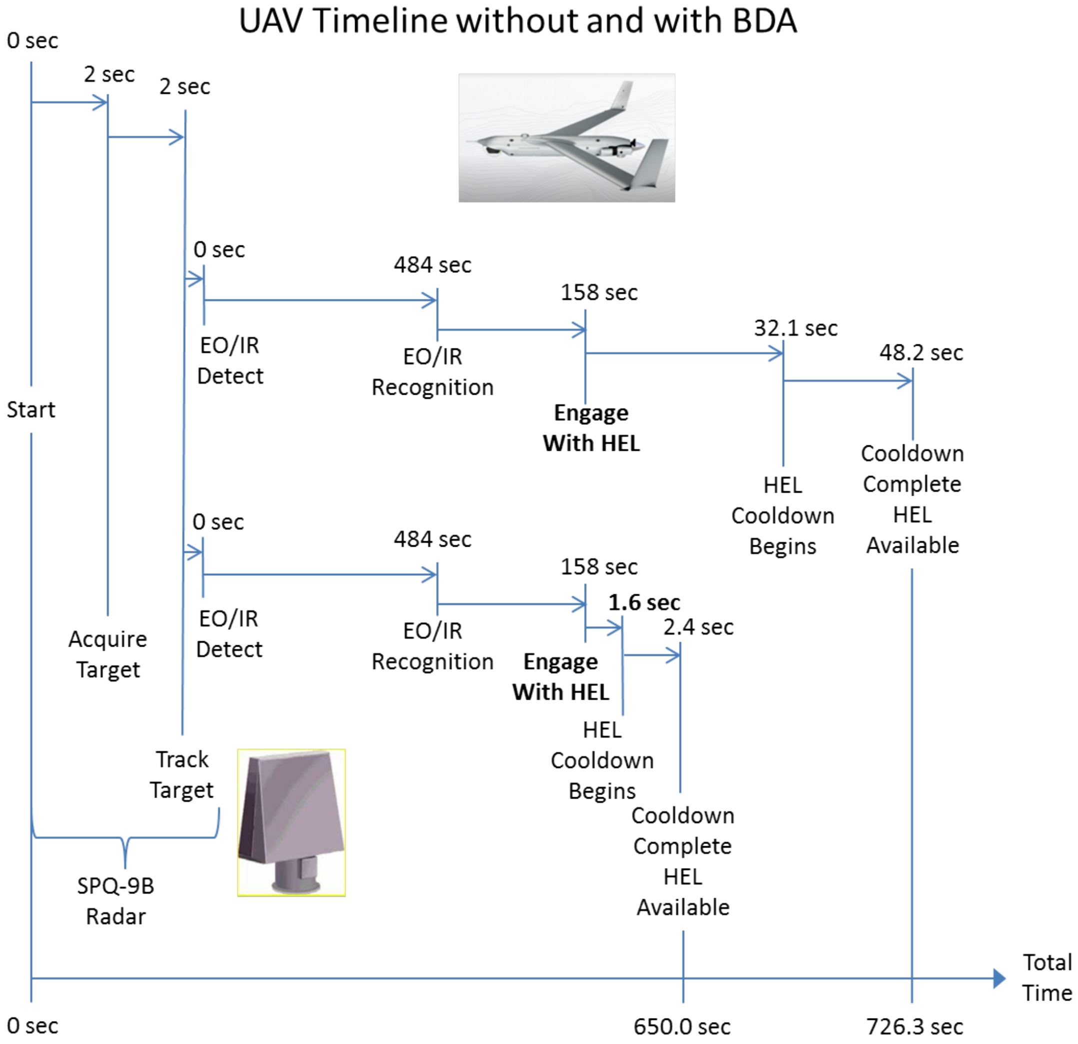

Figure 38. HEL-UAV Engagement Time Sequence

2. How is dwell time calculated for a HEL and how can this time be optimized for the HEL Combat System?

Dwell Time is calculated in the BOE model using a lethal fluence equation which takes the HEL lase time (seconds) for mission kill and adds the time it takes for the threat to fall from its “attack height” to the water (seconds). This provides the time for hard kill in the model. This calculation supports the definition of hard kill where a HEL engagement may continue until the target falls into the water, explodes or disappears.

In the combat system architecture, dwell time is a predicted value that interfaces with the combat system functions "prioritize threats" and "schedule weapons." This predicted value supports weapon scheduling for a prioritized list of threats.

Dwell time can be optimized through an interface with BDA. This interface will provide data to adjust the dwell time from a dwell time that is necessary to achieve a hard kill to only that which is necessary to achieve a mission kill.

3. What are the expected cost benefits of implementing the BDA system?

According to an open source article about the testing of the U.S. Navy's LaWS, a cost comparison of the laser weapon versus the SM-2 shows a $1 to $400,000 operation cost difference (Stratfor Global Intelligence 2014).

Another source of weapon cost is provided in Table 27 below. At $0.63 per shot, the LaWS has the lowest operational cost.

Table 27. Laser Weapon System Operational Costs (after FAS 2014; Oestergaard 2014)

System Name	Operational Cost
SM-2	$400 K per shot
ESSM	$840 K per unit (quad pack)
LaWS	$0.63/shot
CIWS	$14 K per salvo at 200 rounds per salvo

Since one dollar per engagement is already a low cost, the addition of BDA was not expected to induce a large cost increase for the HEL combat system. The benefit of the BDA system on engagement cost is that it provides more kills per swarm engagement than a HEL without BDA.

4. Does a BDA system on a HEL Combat System provide more mission kills than a HEL Combat System without a BDA system, given a threat scenario or scenarios?

Yes, the addition of the BDA system adds more mission kills per threat scenario when compared to the baseline combat system without BDA. These scenarios are detailed in Appendix A.

Figure 39 depicts total kills by the Combat System in each scenario with BDA off and BDA on. Each scenario demonstrated improvement with BDA on regardless of the respective numbers of HEL and Phalanx CIWS mounts. Scenario 4 included two Phalanx CIWS mounts and two LaWS mounts with BDA enabled. The Combat System successfully defeats all 50 incoming threats with this weapons configuration.

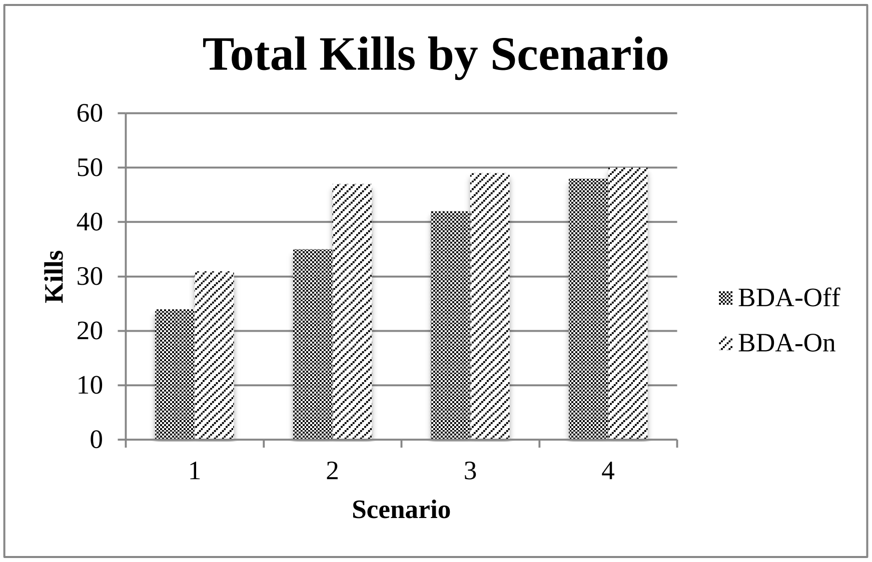

Figure 39. Total Kills by Scenario

Figure 40 compares the number of HEL-only kills per scenario with BDA off and BDA on. The largest improvement is in Scenario 2. This scenario resulted in 11 more HEL kills versus a notional threat set containing only UAV/UCAV and small boats with BDA on. Based on the experimental results depicted in these figures, the real-time BDA system increases ship survivability in an asymmetric threat environment.

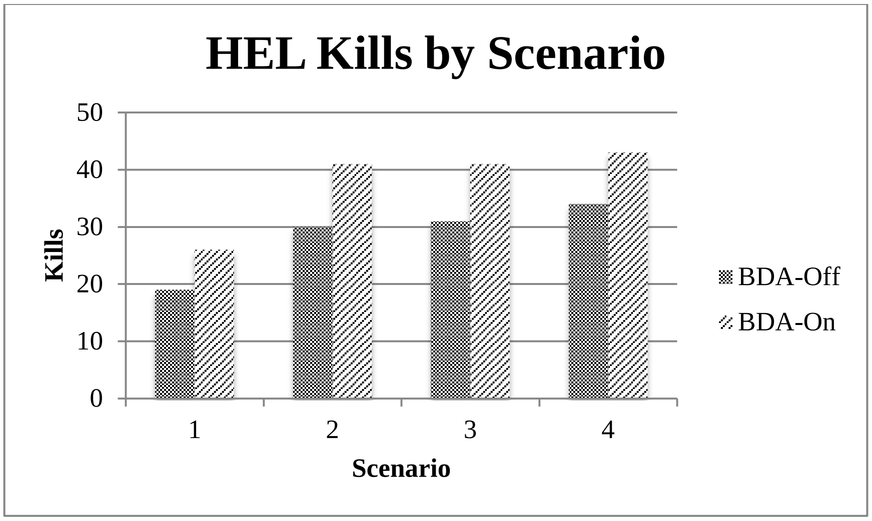

Figure 40. HEL Kills by Scenario

5. How would the BDA system be integrated into an existing HEL Combat System?

BDA would become integrated with the combat system through either a hardware or software interface. Software seems to be the likely method for integration though that solution means greater system complexity. A hardware solution would still require some sort of software interface to communicate with the combat system interfaces. Any software developed for the BDA system should be self-contained so that it is isolated from external influence

C. RECOMMENDATIONS AND CONCLUSIONS

The design concept in the M&S proved that the BDA system did in fact provide an increased survivability of the ship and her crew through an increased number of HEL kills and Total Overall kills. Based on these results, the concept needs further analysis with a more detailed model along with detailed engagement scenarios. The following technical issues for a BDA system would need to be considered and evaluated in a more detailed model:

1. Develop a method to differentiate between live threats, debris and assets to avoid fratricide and unnecessary engagements.
2. Provide an identification method for mission kills.
3. Develop an accurate Probability of Kill for each weapon-threat pair.

4. Develop an accurate BDA criteria database for each weapon-threat pair based on organic sensor inputs.
5. Improve detection methods for small boat kinematic changes.

The HEL BDA Team believes that a BDA system is needed in the twenty-first century battlespace to counter the increasing threat of swarm attacks and other asymmetrical threats in the littorals.

APPENDIX A. SIMULATION SCENARIOS

A. BOE SIMULATION SCENARIOS

The BOE Model and simulation was executed with four scenarios with each with BDA off and BDA on. The goal of these runs was to establish a baseline for each setup that would be used to compare to data run with the ExtendSim scenarios. Each of the following was run 1000 times with BDA off and on. The results were then compared to determine the change in number of kills. In each scenario 50 random targets were generated to stress the system.

Scenario 1 – The random targets were generated from the following target list:

1. Missile
2. UAV
3. UCAV
4. Boat

The ship load-out was one HEL and one CIWS.

Scenario 2 – The random targets were generated from the following target list:

1. UAV
2. UCAV
3. Boat

The ship load-out was one HEL and one CIWS.

Scenario 3 – The random targets were generated from the following target list:

1. Missile
2. UAV
3. UCAV
4. Boat

The ship load-out was two HELs and two CIWS.

Scenario 4 – The random targets were generated from the following target list:

1. UAV
2. UCAV
3. Boat

The ship load-out was two HELs and two CIWS.

B. EXTENDSIM SCENARIOS

Modeling and simulation executes three scenarios: baseline, stress, and swarm. These scenarios are coded in ExtendSim with and without BDA. The baseline scenario verifies the model to ensure that it functions as intended. Data from the stress and the swarm scenarios are then analyzed to compare the effectiveness of BDA implementation. The following subsections explain the scenarios.

(1) Baseline Scenario

The baseline scenario breaks down into two parts. In the first part, the model simulates separate attacks by ASMs, UAVs, UCAVs, and FACs. In the second part, the model simulates simultaneous attacks by these four threats. These two sub-scenarios verify the model.

(2) Stress Scenario

The stress scenario simulates the performance of the weapon systems against large numbers of targets. Scenarios with 50 missiles and 50 suicide boats stress the HEL combat system as modeled in ExtendSim. If 50 targets do not overwhelm the weapon systems, the number of targets can increase to 65, 75 or 100 until the system is overloaded.

(3) Swarm Scenario

The swarm scenario simulates multiple threat types attacking the ship simultaneously. This scenario will test the prioritizing of different targets. Missiles, UAVs, UCAVs, FACs and explosive boats have different radar cross-section and different incoming speed. Baseline and stress scenarios are not enough to model real-life scenario. In the swarm scenario, there will be ten missiles, five FACs, five explosive motorboats, two UAVs, and two UCAVs.

C. THREAT DATA FOR MODELING AND SIMULATION

1. Anti-Ship Missiles

a. Noor-2 Anti-Ship Missile:

Range: 120 km

Length: 6.5 m

Speed: 306 m/s

Warhead: 165 kg (FAS 2000; Wright 2010)

Noor-2 is Iranian production of the Chinese C-802/YJ-8 missile. It is the most common missiles in the Iranian navy's arsenal. C-802 is improved version of C-801 (Iranian Noor-1). China developed the C-801 design from the French Exocet missile (Open Source Intelligence Project 2011, 70). The C-802 design replaced the C-801's solid rocket engine with a turbojet engine (FAS 2000), giving it a subsonic speed of 0.9 mach. The weight decreased from 815 kg to 715 kg and the range increased from 42 km to 120 km. The C-802 has data link allowing OTH targeting (Open Source Intelligence Project 2011, 71). It has the same warhead size of 165 kg as C-801. This size is capable of sinking CGs and DDGs (i.e., U.S. CG-47 Ticonderoga class and DDG-51 Arleigh Burke class). During the final design flight tests, one C-801 missile attacked and sank a target ship with displacement of 10,000 tons (FAS 1999b). A Ticonderoga class cruiser is 9,600 tons (U.S. Navy 2014b). C-802 is estimated to have a hit probability of 98 percent (FAS 2000), due to the low altitude attack at five meters (Open Source Intelligence Project 2011, 71) above sea surface and strong anti-jamming capability. Iran is further developing missile system technology with help from other county (Cordesman 2007, 117). Future upgrades may include dual IR and radar seekers, a laser altimeter and GPS guidance (Open Source Intelligence Project 2011, 71). Noor is very versatile. Different variants can be launched from air, land, or sea. It is considered among the most capable ASMs alongside U.S. Navy Harpoons.

b. Kosar Anti-Ship Missile

Range: 25 km

Length: 2.5-2.7 m

Speed: 265–290 m/s

Warhead: 29–30 kg (FAS 1999a)

Kosar or Kowsar is the little brother of Noor. Kosar refers to several ranged ASMs types of Chinese origin, C-701 variants and TL-10 (Open Source Intelligence Project 2011, 72). Kowsar is the light ASM in the Iranian arsenal. While Noor was designed to attack large warships, Kosar missiles are designed for smaller targets, but we cannot disregard them as a threat against larger warships. Kosar can be launched from land, air, or sea. Some Iranian FACs can carry these ASMs. Kosar does not climb to enter a cruise phase after launch; it remains at a constant height of about 15 m. Once it enters the vicinity of the target, it switches over to operator control by television seeker or radar. Infrared seeker may be in development (Wright 2010).

c. Nasr Anti-Ship Missile

Range: 35 km

Length: 3.5 m

Speed: 306 m/s

Warhead: 130 kg (Open Source Intelligence Project 2011, 74)

Nasr is Iranian production of the Chinese C-704 missile, a scaled-up version of C-701. Nasr is half of the size of Noor and slightly larger than Koswar and twice the weight but can still be carried by some FACs that are capable of launching Koswar missiles. It is a medium-ranged weapon that can be launched from air, land, and sea. With 130kg, armor piercing warhead, Noor is capable of destroying targets displacing 4,000 tons (UPI 2010). It is capable of delivering significant damage to large warships. It can be equipped with active radar seeker or gimbaled TV and imagining infrared seekers (Andrew and Kopp 2014; GlobalSecurity.org 2011h).

d. Harpoon Anti-Ship Missile

Range: 140 km

Length: 3.85 m

Speed: 272 m/s

Warhead: 221 kg (Open Source Intelligence Project 2011, 75)

Harpoon RGM-84, surface launched variant of the missile was once a part of the Iranian arsenal. RGM-84 missile were expended during the Iran-Iraq war. In the mid-1990s C-802 launchers replaced the Harpoon launchers onboard missile crafts. In 2010 Harpoon launchers reappeared on a Kaman class boat indicating that Iran has found a source of Harpoon missiles or had begun producing them. (Open Source Intelligence Project 2011, 75).

2. Unmanned Aerial Vehicle

The following information on UAVs is from open-sources. The validity may be inaccurate. UAVs are a growing threat. From 1980s to present day, UAV Iranian technology has grown exponentially with indigenous research and technologies from other counties. Iran has reported obtaining several U.S. drones. Capabilities started with short-range aerial reconnaissance drone and developed into long-ranged attack drones that are able to carry precision strike missiles

a. Mohajer

Mohajer-I UAVs are the first Iranian drones with any capabilities beyond serving as aerial targets. Mohajer was used for reconnaissance, jamming, and communications missions. These are launched by a rail system and recovered by parachute (Naval Drones 2012). In the 1990s, Mohajer was reported to have carried rocket-propelled grenades, making it one of the earliest UCAVs (Mashregh News 2011b; GlobalSecurity.org 2001i). In the early 2000s Mohajer-IV was announced. It was reported to have wingspan of 5.3 m, operational range of 150 km and/or seven hours of flight time (Cordesman 2007, 65). IRGC claimed Mohajer-IV has a top speed of 120 mph (53.6 m/s) and a ceiling of 15,000 ft (4572 m) (Mashregh News 2011b).

b. Ababil

Ababil has several variants. Ababil-5 is a medium-range reconnaissance and surveillance UAV; Ababil-T is a short/medium-range attack UAV. Ababil-B and –S are designed for ISR operations (Cordesman 2007, 65; GlobalSecurity.org 2011a). Izz ad-

Din al-Qassam Brigades, the military wing of Islamic Resistance Movement Hamas shared images of Ababil-1 carrying four AGM-114 Hellfire ASM, each with an 8–9 kg warhead (Cenciotti 2014). Ababil-1C was designed for suicide missions (Binnie 2014a). Ababil could be launch with a pneumatic launcher or a rocket launch system. It could be launched from a truck or ship deck. According to Fars News Agency's exposition in 2014, Ababil-3 has an operational radius of 100 km, operational speed up to 55.6 m/s, and a service ceiling of 5,000 m with four hours of flight time (Army Recognition 2014; Binnie 2014a). The United States military identified the Ababil-3 to be 3.2 m (Nordland and Rubin 2009).

c. Ra'ad 85

Announced in 2013, According to Iranian Army Ground Force Brigadier General Ahmad Reza Pourdastan, Iran developed and produced a new suicide drone, Ra'ad 85. It is a remotely piloted drone capable to destroying both moving and fixed targets; it is a precision-guided munition. The UAV is capable of carrying different warhead sizes depending on its intended target (Cenciotti 2013b). It was claimed to have a range of 100 km (Uskowi 2013).

d. Yassir

On December 5, 2012, Iran's Revolution Guards Corps (IRGC) Navy Commander Rear Admiral Ali Fadavi announced that they had captured a Boeing Insitu ScanEagle drone that had violated Iranian airspace. On September 28, 2013, IRGC announced the Yassir, based on the ScanEagle (Cenciotti 2013a). Detailed information about the Yassir is not yet available via open sources. It is safe to assume its capabilities are very close to that of the ScanEagle. According to the Insitu website, ScanEagle has a wingspan of 3.11 m and a total length of 1.55 m. It is capable of reaching flight ceiling of 6 km and a max speed of 41.2 m/s.

e. Karrar

Iran unveiled its first domestically manufactured long-ranged combat drone, the Karrar, in August 2010. It is reported to have and operational range of 1,000 km and can carry two 115-kg bombs or precision-guided munitions (Press TV 2013), capable of carrying Nasr and Kosar. It is reported to have a wingspan of 3 m, a length of 5.51 m and a top speed of 264 m/s with service ceiling of 12 km and a range of 1000 km (Mashregh News 2011a; Defense Update 2011).

f. *Fotros*

On November 18, 2013, Iran unveiled its biggest indigenously developed drone, which can be used for reconnaissance and combat operations. The remote-controlled aircraft, dubbed Fotros, has an operational radius of up to 2,000 km, an operational altitude of 25,000 ft and flight endurance of up to 30 hours (Press TV 2013).

3. Maritime Threats

The following section presents some possible surface threats that are in Iran's navy. This is not a complete list of Iranian assets. The following section lists some FACs that are currently in-service and/or in production. FACs are small fast, offensive warships that can reach speeds greater than 25 knots. FACs operates in close proximity to land. Listed are some FACs, which include missile crafts, patrol crafts, MLRS crafts and torpedo boats. Specifications and number of assets are estimated values from open-source. Exact information is unknown.

a. *Kaman/SINA Class Missile Craft*

(Open Source Intelligence Project 2011, 32; GlobalSecurity.org 2011g):

Displacement: 275 tons
Length: 47 m
Beam: 7.1m
Draft: 1.9 m
Speed: 19.3 m/s

Armament: (4) C-802 "Noor" ASM
(1) 76 mm OTO-Melara Naval Gun
(1) 20 mm Gun

Iran purchased 12 Kaman class missile crafts from France between 1974 and 1981 (Open Source Intelligence Project 2011, 32). These missile crafts were originally fitted with U.S.-supplied Harpoon missiles. However, Harpoon missiles were depleted during the Iran-Iraq war. Four C-802/Noor ASM launchers then replaced the Harpoon launchers.

In 2006 the indigenous SINA class entered service. As of 2010 there are 12 in service and several under construction (Open Source Intelligence Project 2011, 32).

b. Thondor Class Missile Craft

(Open Source Intelligence Project 2011, 34; GlobalSecurity.org 2011j);

Displacement: 205 tons
Length: 33.6 m
Beam: 7.6 m
Draft: 2.7 m
Speed: 18 m/s

Armament: (4) C-802 “Noor” ASM
(2) 30 mm Gun
(2) 23 mm Gun

Thondor class missile craft was a renamed Chinese Houdong missile craft. Houdong is a copy of the Russian Osa class missile crafts (GlobalSecurity.org 2011j). Iranian navy had imported at least ten Houdong missile crafts (Chang 2007; Binnie, 2014b). The exact number in service is unknown; however, some sources indicated as many as 40 vessels (Gertz and Scarborough 2002).

c. C-14 “China Cat” Missile and MLRS Craft

(U.S. Naval Institute 2012):

Displacement: 19 tons
Length: 13.75 m
Beam: 4.8 m
Draft: 0.7 m
Speed: 25.7 m/s

Armament: (2) Nasr ASM
or (4) Kosar ASM
(1) 107 mm MLRS
(1) 23 mm Gun
(1) 12.7 mm Machine Gun

These versatile craft are Chinese imports. Some vessels have been configured without missiles in order to carry the larger MLRS. According to multiple sources, these missiles crafts can carry up to eight Kosar ASMs (Gertz and Scarborough 2002). Originally ten of these armed catamarans were ordered from Chinese manufacturers in 2002 (Open Source Intelligence Project 2011, 35). In 2007, it was reported that 15 new modified China Cats are under construction (U.S. Naval Institute 2012).

d. MK 13 Patrol Craft

(Open Source Intelligence Project 2011, 36):
Armament: (2) Kosar ASM
(2) 234 mm torpedo tubes

The dimension of this unit is unknown. One can speculate that it is similar to that of a China Cat. Approximately there are ten in service (Open Source Intelligence Project 2011, 36; U.S. Naval Institute 2012). According to U.S. Naval Institute, these mono-hull patrol crafts can be fitted with two Nasr and two 324 mm torpedo tubes.

e. Kajami Submersible Torpedo Boat

(Open Source Intelligence Project 2011, 36):
Displacement: 10.5 tons
Length: 20 m (25)
Beam: 2.95 m
Draft: 3 m
Speed: 20.6 m/s
Armament: (2) 324 mm Torpedo Tubes

Kajami is rebadged Taedong-B, produced by North Korea. The above dimensions are estimated from previous generations of submersible boats. Taedong-B is more evolved than the original I-SILC, improved-submersible infiltration landing craft; the newer craft can fully submerge 3 m below the surface (Open Source Intelligence Project 2011, 38; Covert Shores Naval Warfare Blog 2010).

f. IPS-18 Tir Class Torpedo Boat

(Open Source Intelligence Project 2011, 38):
Displacement: 28.16 tons
Length: 21.12 m
Beam: 5.77 m
Draft: 0.87 m
Speed: 20.6 m/s
Armament: (2) 533 mm Torpedo Tubes
(1) 12.7 machine gun

IPS-18 was of North Korean origin. These small FACs are designed with radar-cross section reduction in mind. They are potentially armed with Shkval rocket torpedo, with a range of approximately 8 km, or North Korean heavy weight torpedo, with a range of approximately 10 km. Iran is said to have produced a version that is capable of carrying Noor ASM (Open Source Intelligence Project 2011, 39).

g. IPS-16 Fast Attack Craft

(Open Source Intelligence Project 2011, 40; Chang 2007):

Displacement: 13.75 tons
Length: 16.3 m
Beam: 3.75 m
Draft: 0.67 m
Speed: 26.7 m/s

Armament: (2) 324 mm torpedo tubes
(2) Kosar ASM
(2) Nasr ASM
(2) 12.7 mm machine gun

The original, low-observable torpedo boat, IPS-16 was imported from North Korea. Iran has locally produced large number in several modified forms. Similar to the IPS-18, these fiberglass boats were designed with signature reduction hull features (Associated Press 2010; Uskowi 2010). The small size, high speed, and low radar signature make these potent adversaries. Depending on the variations the crafts could be armed with ASMs, torpedoes, and machine guns. Some IPS-16s are equipped with MLRS. Figure 41 below shows the IPS-16 FAC family. There are approximately 40 IPS-16 FACs in service with many more in production (Open Source Intelligence Project 2011, 13).

h. Gahjae—Semi-submersible Torpedo Boat

Gahjae is also known as Taedong-C. It carries two 324 mm torpedo tubes. Gahjae was the first IPS-16 that delivered to Iran from North Korea. The lightweight torpedoes are not capable of sinking large warships, but they can effect mobility kills (Open Source Intelligence Project 2011, 40).

i. Peykaap—Torpedo Boat

Peykaap carries two 324 mm torpedo tubes. Peykaap is similar to Gahjae. However, Peykaap is not submersible and it is 1 m shorter than Gahjae at 16 m (FAS 2009).

j. Bavar—Missile and Torpedo Boat

Bavar is a modified Peykaap, sometimes referred to as the Peykaap-II. It carries a 12.7 mm machine gun and two Kosar ASMs or two 324 mm torpedoes. The additional armament significantly reduces its stealth profile (FAS 2009).

k. Zolfaghar—Missile Craft

Zolfaghar is the latest version of IPS-16 with an extended 20 m hull. The lengthened hull enables Zolfaghar to carry two Nasr ASMs. Nasr are slightly larger than the Kosar ASMs carried by Bavar. Zolfaghar is a replacement for the outdated China Cat (Open Source Intelligence Project 2011, 40; FAS 2009).

l. Dalaam/Tarlan Class Semi-submersible Torpedo Boat

(Open Source Intelligence Project 2011, 43):

Displacement: 8.5 tons
Length: 11.9 m
Beam: 3.1 m
Draft: 1.5 m
Speed: 29.8 m/s

Armament: (1) 533 mm torpedo tubes
(1) 12.7 mm machine gun

Tarlan and Dalaam are semi-submersible catamarans with aluminum hulls (Open Source Intelligence Project 2011, 42). These small torpedo craft can fire Hoot heavyweight torpedoes. The Hoot design is based on the very capable Russian Shkval torpedo. It has a range of 11–15 km carries a 700 kg warhead (Open Source Intelligence Project 2011, 43).

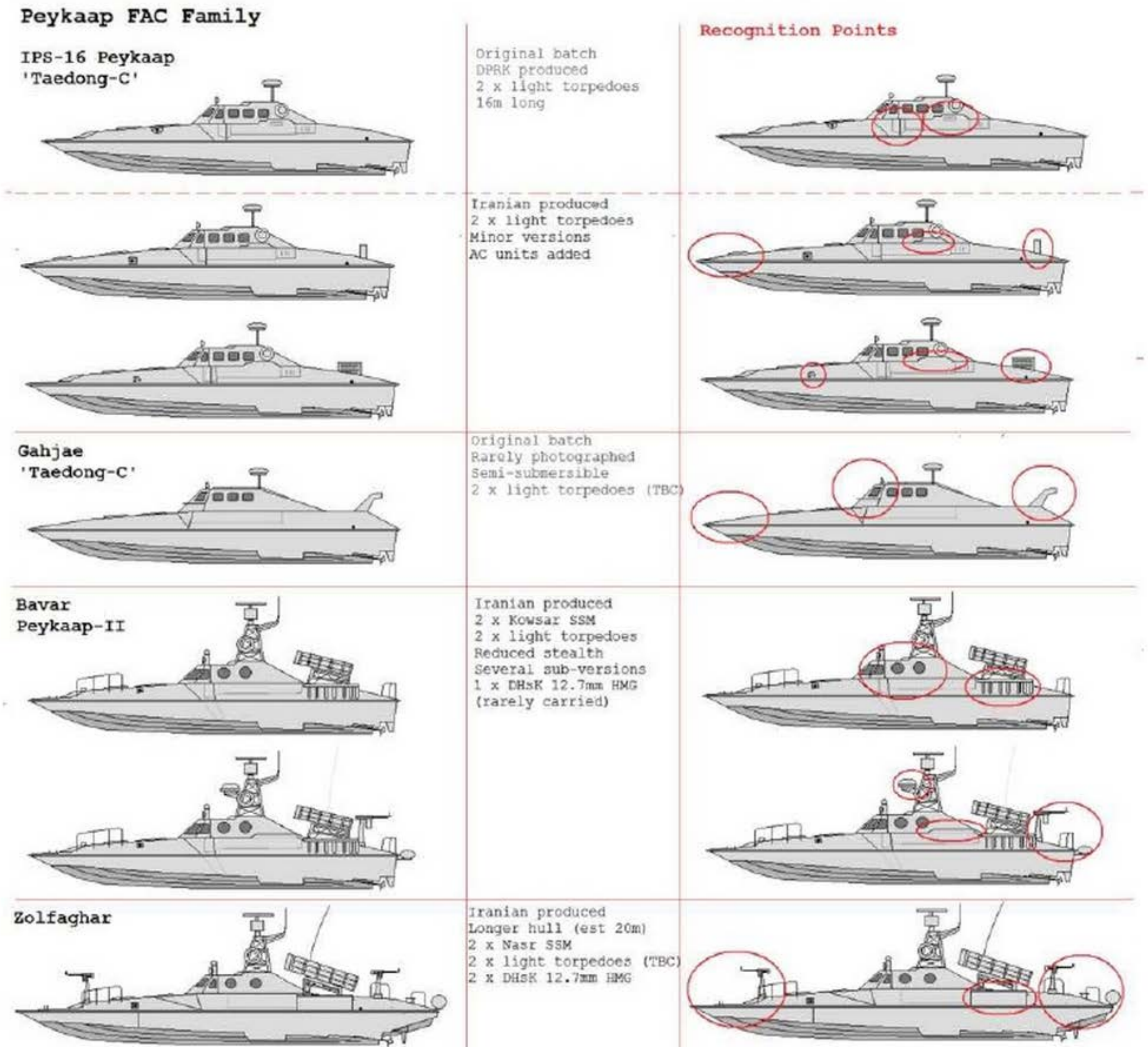

Figure 41. IPS-16 FAC Family (from Open Source Intelligence Project 2011, 4)

m. *Explosive Motor Boat (Typical)*

(Open Source Intelligence Project 2011, 44):

Armament: 500 kg shaped charge

Length: 9 m

Beam: 2.2 m

Height:2.1 m

Speed: 19.5 m/s

The top speed is an estimate based on several commercial speedboats with twin 250-hp motors. Boats with two 250-hp motors have speeds range from 36–40 knots.

Explosive motorboats deliver their payload by ramming into the target, not to be confused with suicide attacks. Special Forces operate these motorboats. The operator escapes on a Jet Ski while the explosive boat continues its path toward the target. Jet Skis are docked near the end of the motorboats (Open Source Intelligence Project 2011, 45).

n. Seraj-1 MLRS boat

(Open Source Intelligence Project 2011, 46):
Displacement: 2.5 tons Armament: (1) 107 mm MLRS
Length: 10.6m (1) 12.7 mm Machine Gun
Beam: 2.9 m
Draft: 0.75 m
Speed: 25.7 m/s

These were built on the British Bladerunner-35 design. Bladerunners were known for their stability, high mobility and speed. The listed specifications are that of Bladerunner-35 except for the speed. While a Bladrunner-35 has a top speed of 80 knots, a Seraj-1 has an estimated speed of 50 knots due to the weight of its armament. The current generation of Seraj-1 carries 107 mm MLRS and a 12.7 mm machine gun (Open Source Intelligence Project 2011, 46). Other system may be added in the future.

o. Fabio Buzzi High Speed MLRS Crafts

The Iranian navy purchased these record-breaking speedboats from Italian manufacturer Fabio Buzzi (FAS 2009). The Iranian navy then reverse-engineered the boats and began indigenous production. Fabio Buzzi boats are some of the fastest vessels in the Persian Gulf (FAS 2009). These are rigid inflatable boat (RIB). Armaments equipped depended on size of the craft.

(1) FB RIB-33 MLRS craft (Open Source Intelligence Project 2011, 47):
Displacement: 3.2 tons Armament: (1) 107 mm MLRS
Length: 10 m
Beam: 2.7 m
Draft: 0.6 m

Speed: 29.3 m/s

(2) FB MIL-40 MLRS craft (Open Source Intelligence Project 2011, 47):

Displacement: 6 tons Armament: (1) 107 mm MLRS
Length: 12.9 m (1) 12.7 mm MG
Beam: 2.6 m
Draft: 0.8 m
Speed: 31.9 m/s

(3) FB MIL-55 MLRS

(Open Source Intelligence Project 2011, 47):

Displacement: 15.3 tons Armament: (1) 107 mm MLRS
Length: 16.4 m (1) 12.7mm MG
Beam: 2.9 m
Draft: 0.8 m
Speed: 35 m/s

p. Torough Class MLRS Craft

(Open Source Intelligence Project 2011, 48; U.S. Naval Institute 2012; GlobalSecurity.org 2011j):

Displacement: 6.4 tons Armament: (1) 107 mm MLRS
Length: 12.8 m (1) 12.7 mm machine gun
Beam: 2.66 m
Draft: 0.9 m
Speed: 23.2 m/s

Torough or “Boghammar” were used in the Iran-Iraq war. These were originally manufactured by a Swedish firm, Boghammar Marin, and delivered to Iran for quick militarization and reproduction. They can be armed with MLRSs, machine guns, RPGs, and mines. These flat-bottomed craft are suitable for marshland operations.

q. Ashura Class

(Open Source Intelligence Project 2011, 49; U.S. Naval Institute 2012):

Displacement: 2.8 tons
Length: 7 m
Beam: 2.3 m
Draft: 0.6 m
Speed: 20.6 m/s

Armament: (1) 107 mm MLRS
(1) 12.7 mm machine gun

Ashura, like Torough, was used in Iran-Iraq war, mostly for mine laying. These were often referred to as “Boston Whaler” due to the similar designed to the commercial firm (Open Source Intelligence Project 2011, 49). Displacement listed above is an estimated value base on various commercial models manufactured by Bostonwhaler with similar dimensions. Speed is an estimated value based on numbers provided by U.S. Naval Institute on similar “Boston Whaler” patrol crafts.

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APPENDIX B. EXTENDSIM MODELS

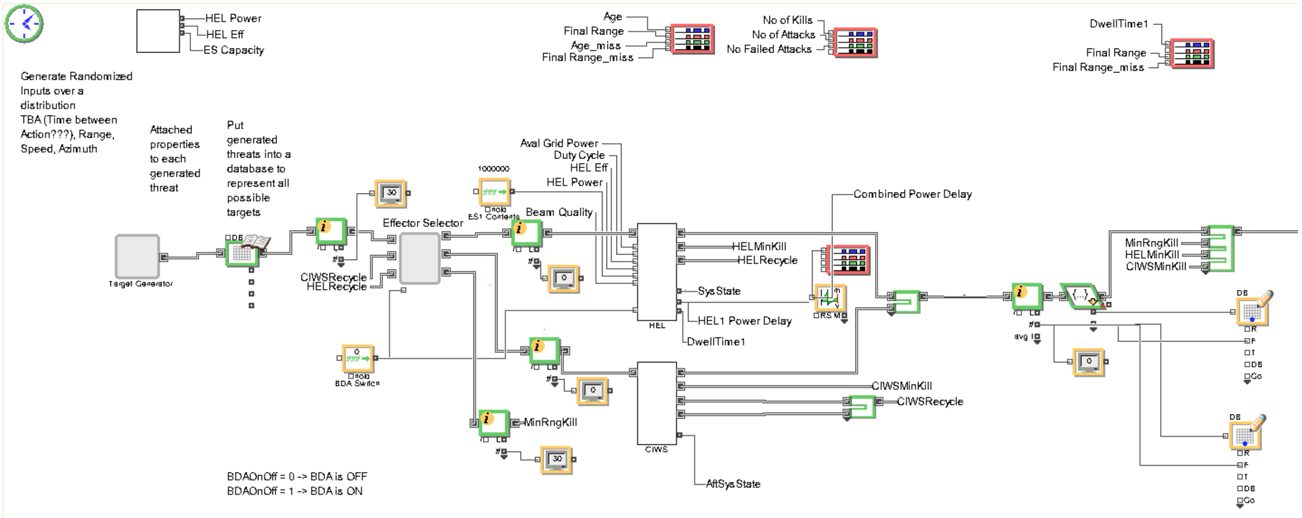


Figure 42. Main Routine

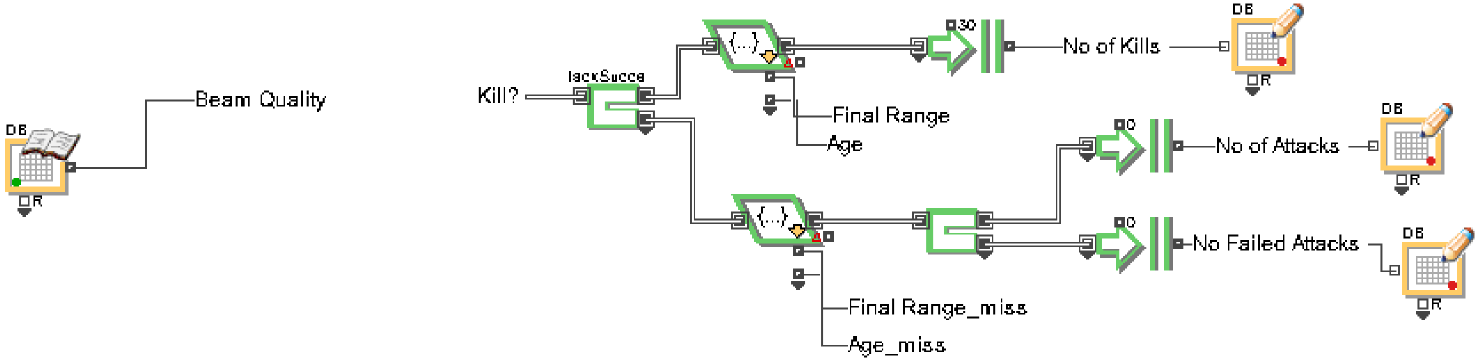


Figure 43. Main Routine Metrics 1

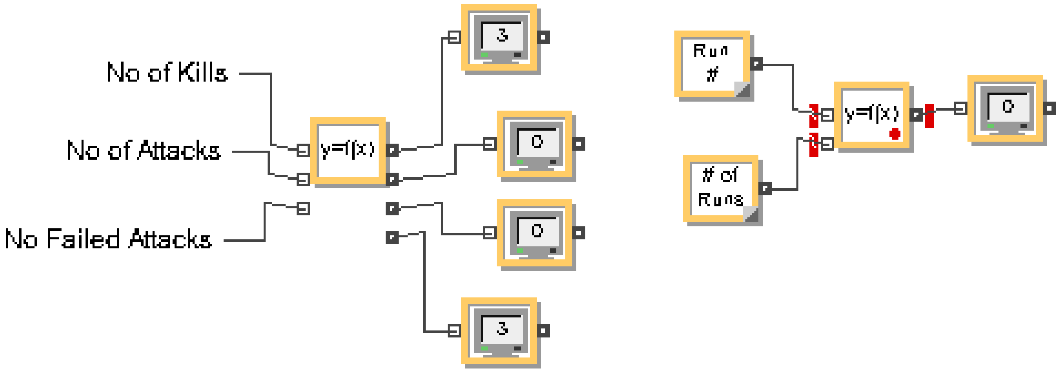


Figure 44. Main Routine Metrics 2

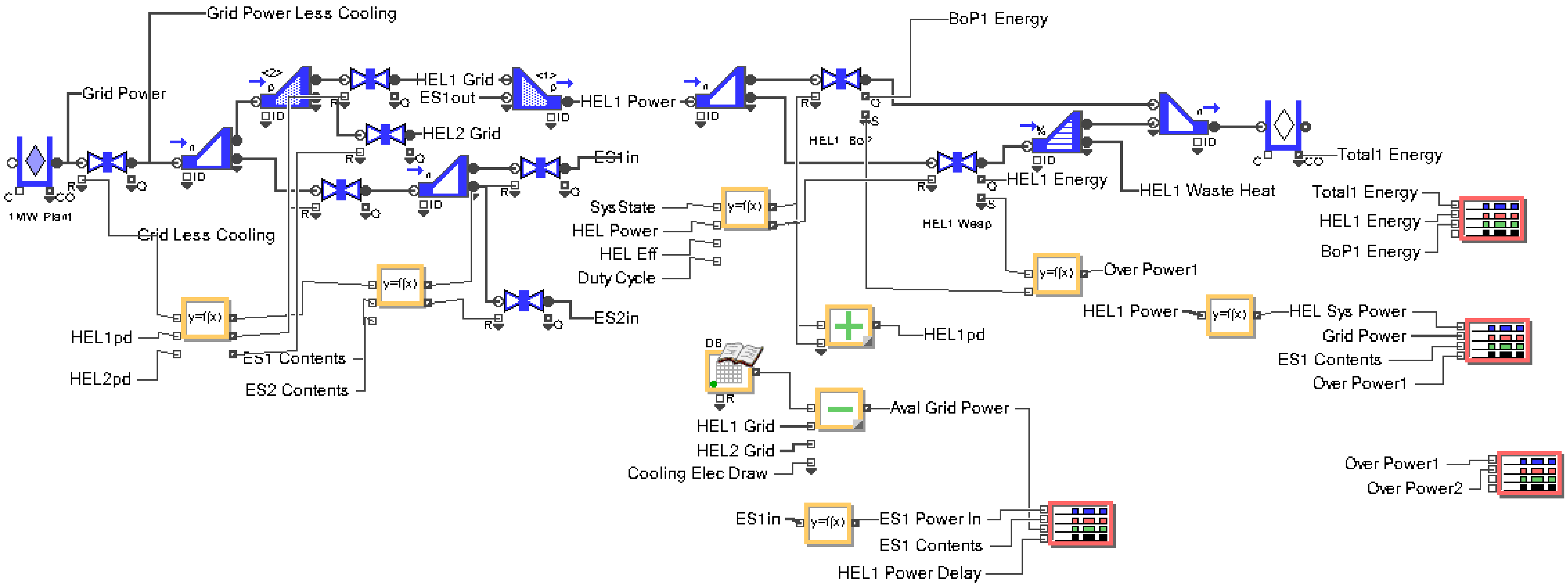


Figure 45. Power Systems 1

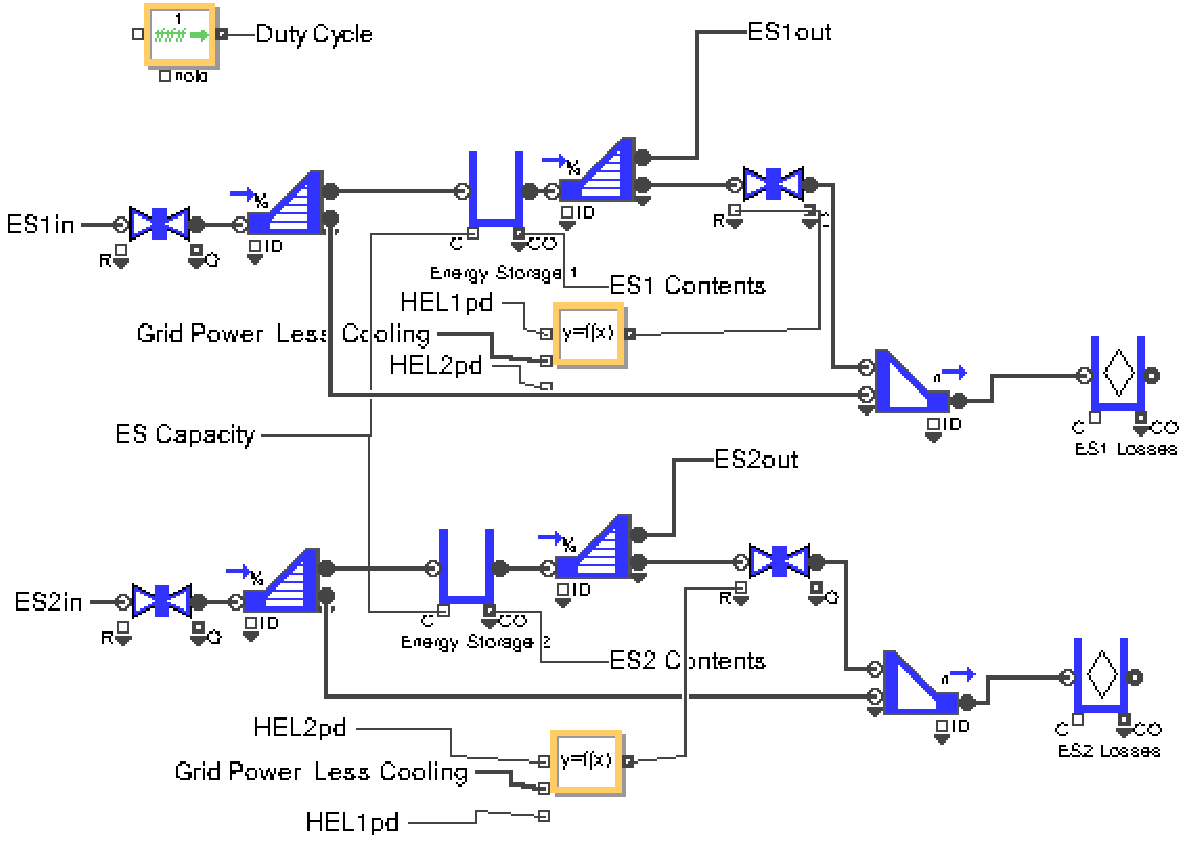


Figure 46. Power Systems 2

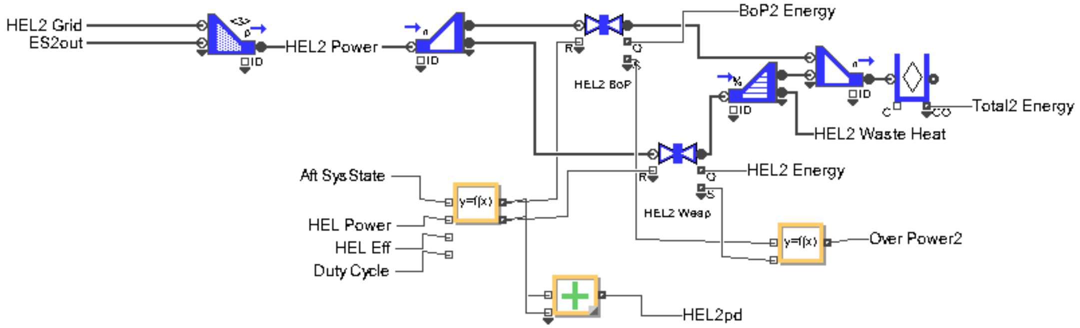


Figure 47. Power Systems 3

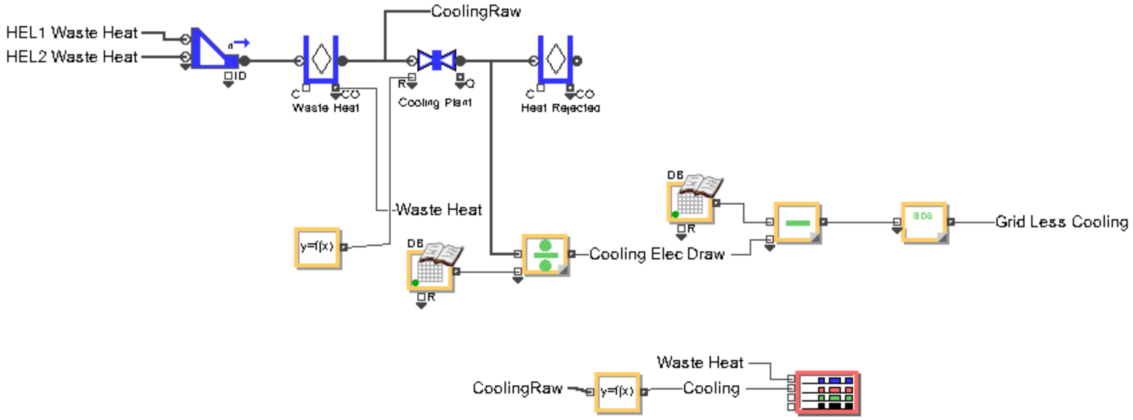


Figure 48. Power Systems 4

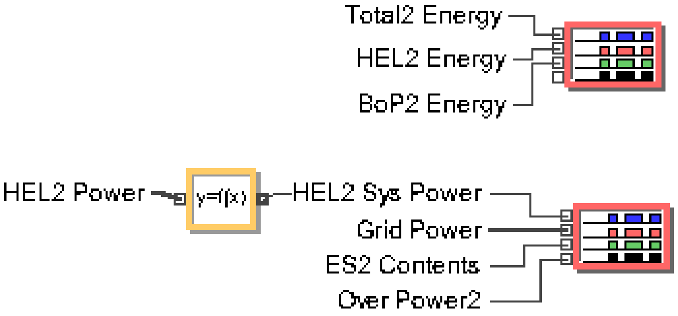
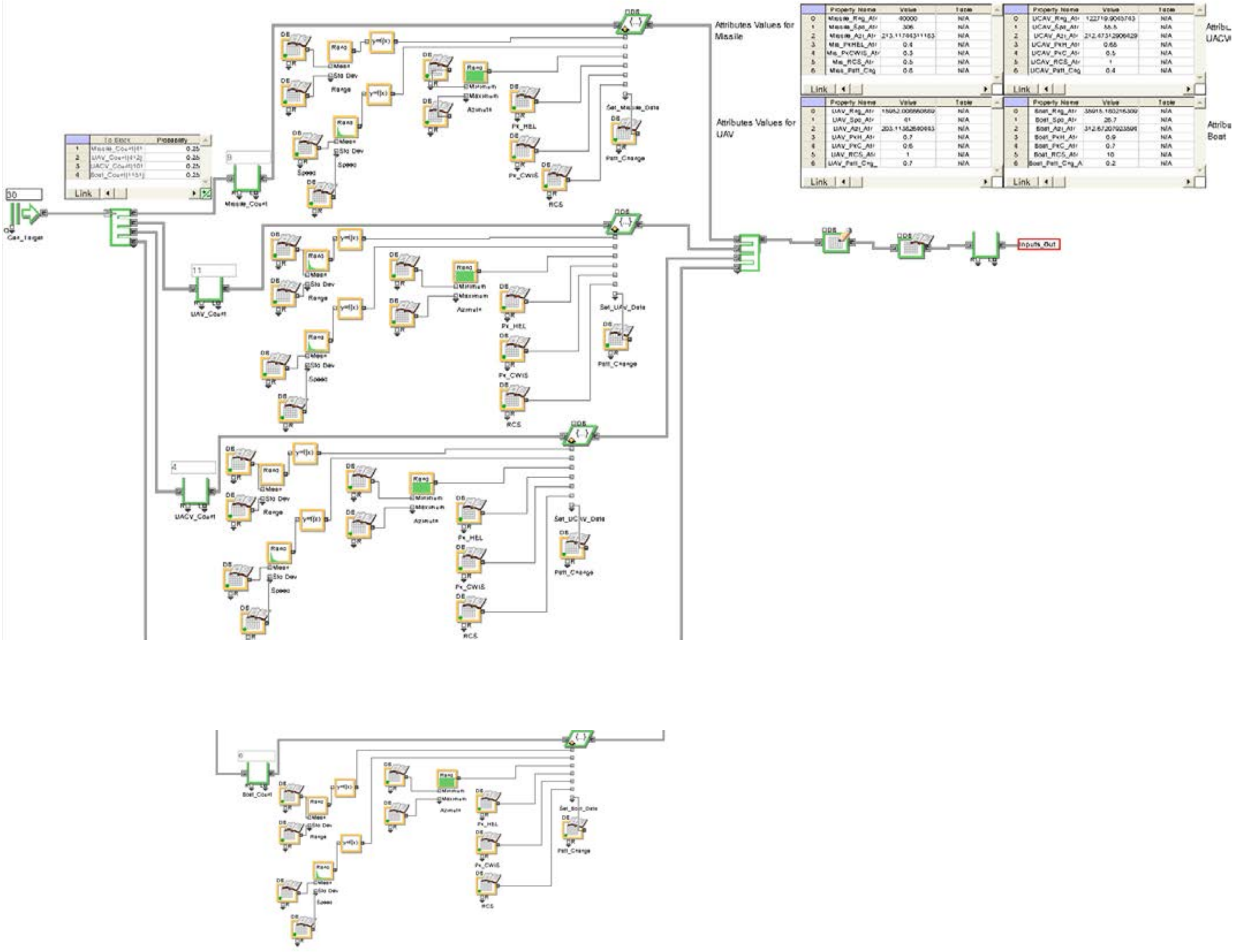


Figure 49. Power Systems 5



	To Block	Probability
1	Missile_Count[6]	0.25
2	UAV_Count[12]	0.25
3	UACV_Count[10]	0.25
4	Boat_Count[11]	0.25

Attributes Values for Missile

	Property Name	Value	Table
0	Missile_Rng_Atr	40000	N/A
1	Missile_Spd_Atr	306	N/A
2	Missile_Azi_Atr	213.117463111163	N/A
3	Mis_PkHEL_Atr	0.4	N/A
4	Mis_PkCWIS_Atr	0.3	N/A
5	Mis_RCS_Atr	0.5	N/A
6	Miss_Patt_Cng	0.6	N/A

	Property Name	Value	Table
0	UCAV_Rng_Atr	122719.9045743	N/A
1	UCAV_Spd_Atr	55.5	N/A
2	UCAV_Azi_Atr	212.4731290629	N/A
3	UCAV_PkH_Atr	0.65	N/A
4	UCAV_PkC_Atr	0.5	N/A
5	UCAV_RCS_Atr	1	N/A
6	UCAV_Patt_Cng	0.4	N/A

Attributes Values for UAV

	Property Name	Value	Table
0	UAV_Rng_Atr	[illegible]	N/A
1	UAV_Spd_Atr	41	N/A
2	UAV_Azi_Atr	203.11382640993	N/A
3	UAV_PkH_Atr	0.7	N/A
4	UAV_PkC_Atr	0.6	N/A
5	UAV_RCS_Atr	1	N/A
6	UAV_Patt_Cng_	0.7	N/A

	Property Name	Value	Table
0	Boat_Rng_Atr	35015.160216309	N/A
1	Boat_Spd_Atr	26.7	N/A
2	Boat_Azi_Atr	312.6720792359	N/A
3	Boat_PkH_Atr	0.9	N/A
4	Boat_PkC_Atr	0.7	N/A
5	Boat_RCS_Atr	10	N/A
6	Boat_Patt_Cng_A	0.2	N/A

Figure 50. Input Generation

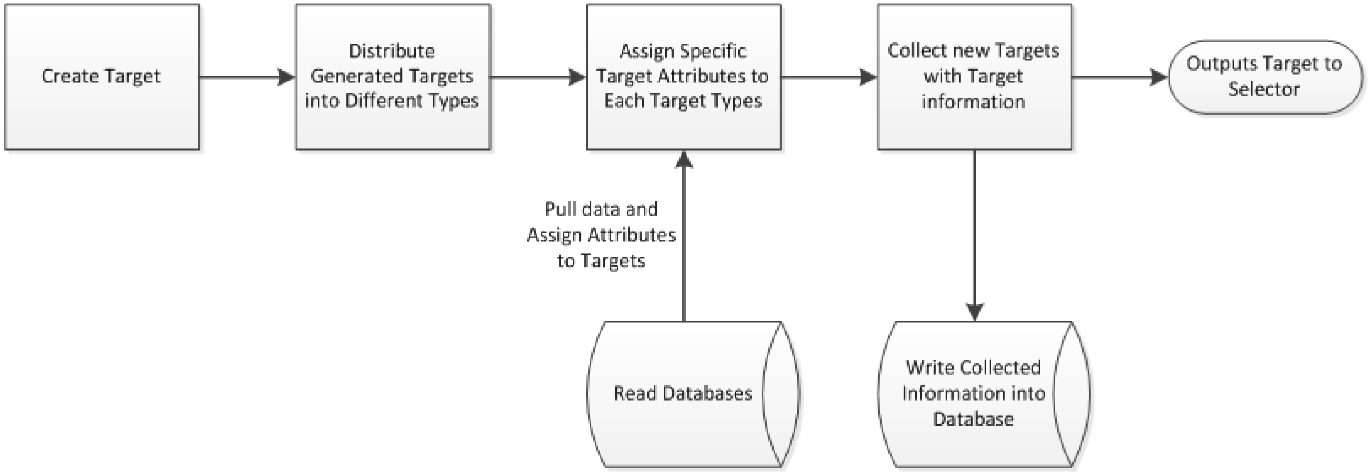


Figure 51. Input Generation FFBD

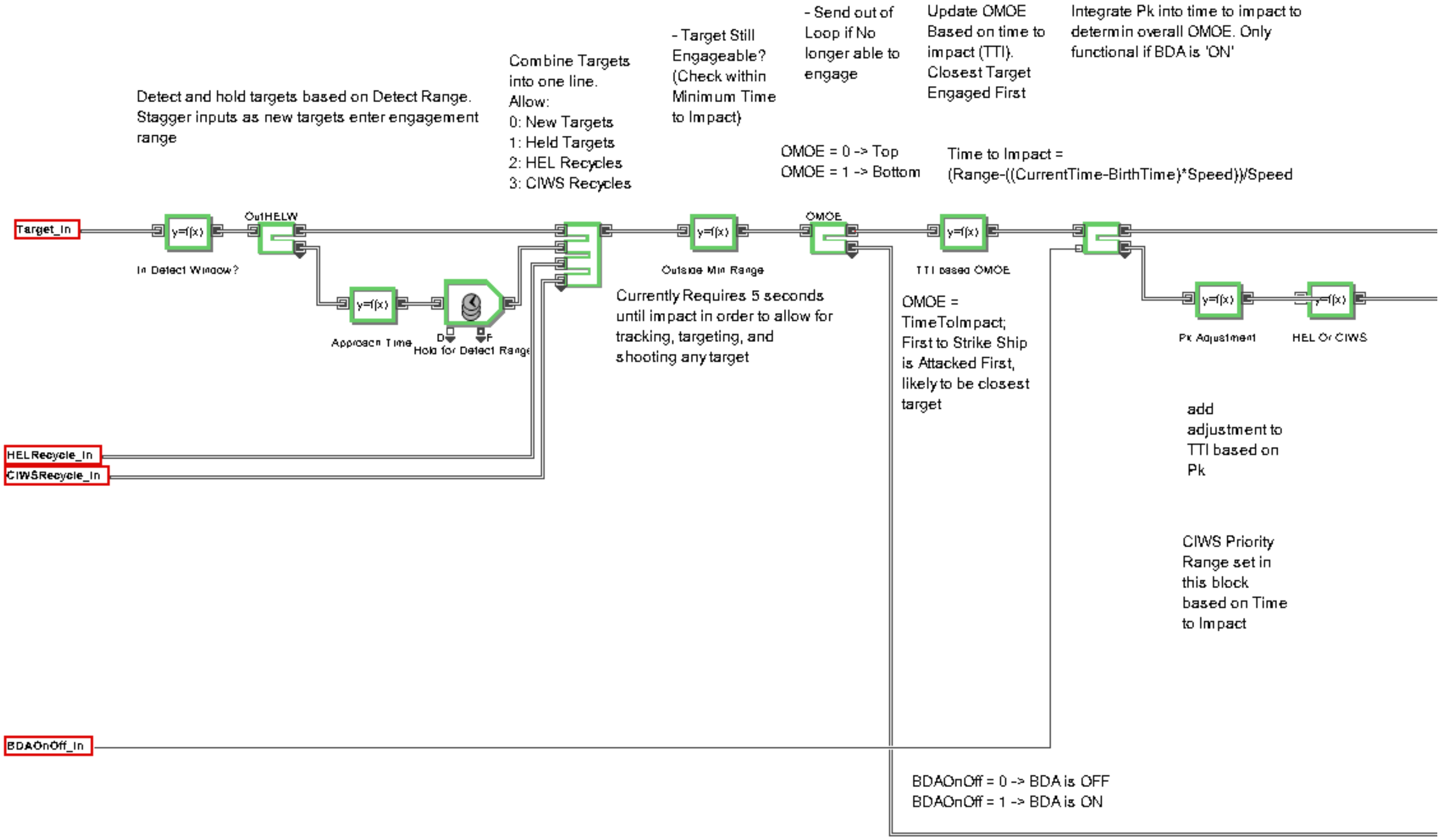
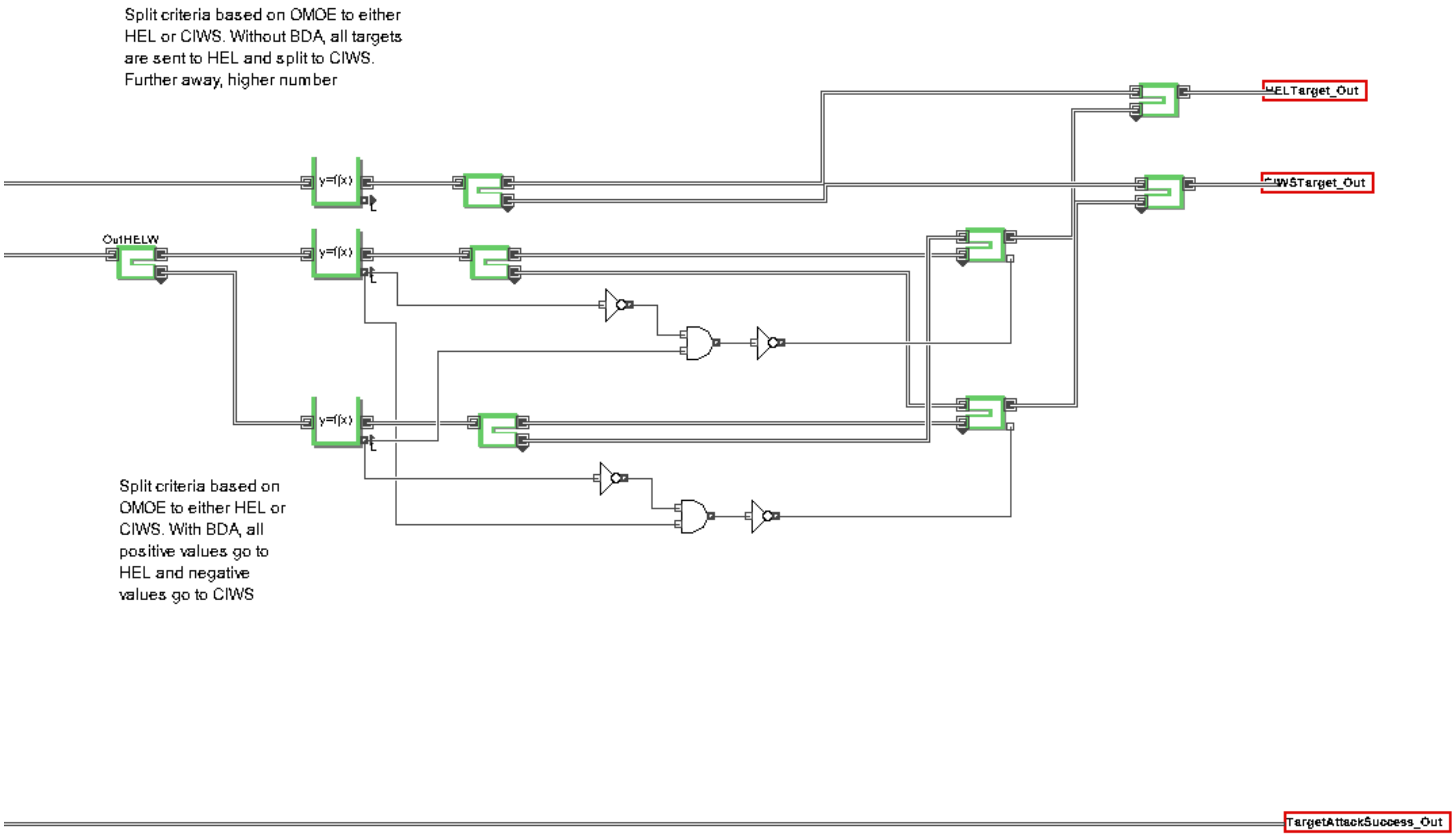


Figure 52. Weapon Selection and Combat System 1



Split criteria based on OMOE to either HEL or CIWS. Without BDA, all targets are sent to HEL and split to CIWS. Further away, higher number

Split criteria based on OMOE to either HEL or CIWS. With BDA, all positive values go to HEL and negative values go to CIWS

Figure 53. Weapon Selection and Combat System 2

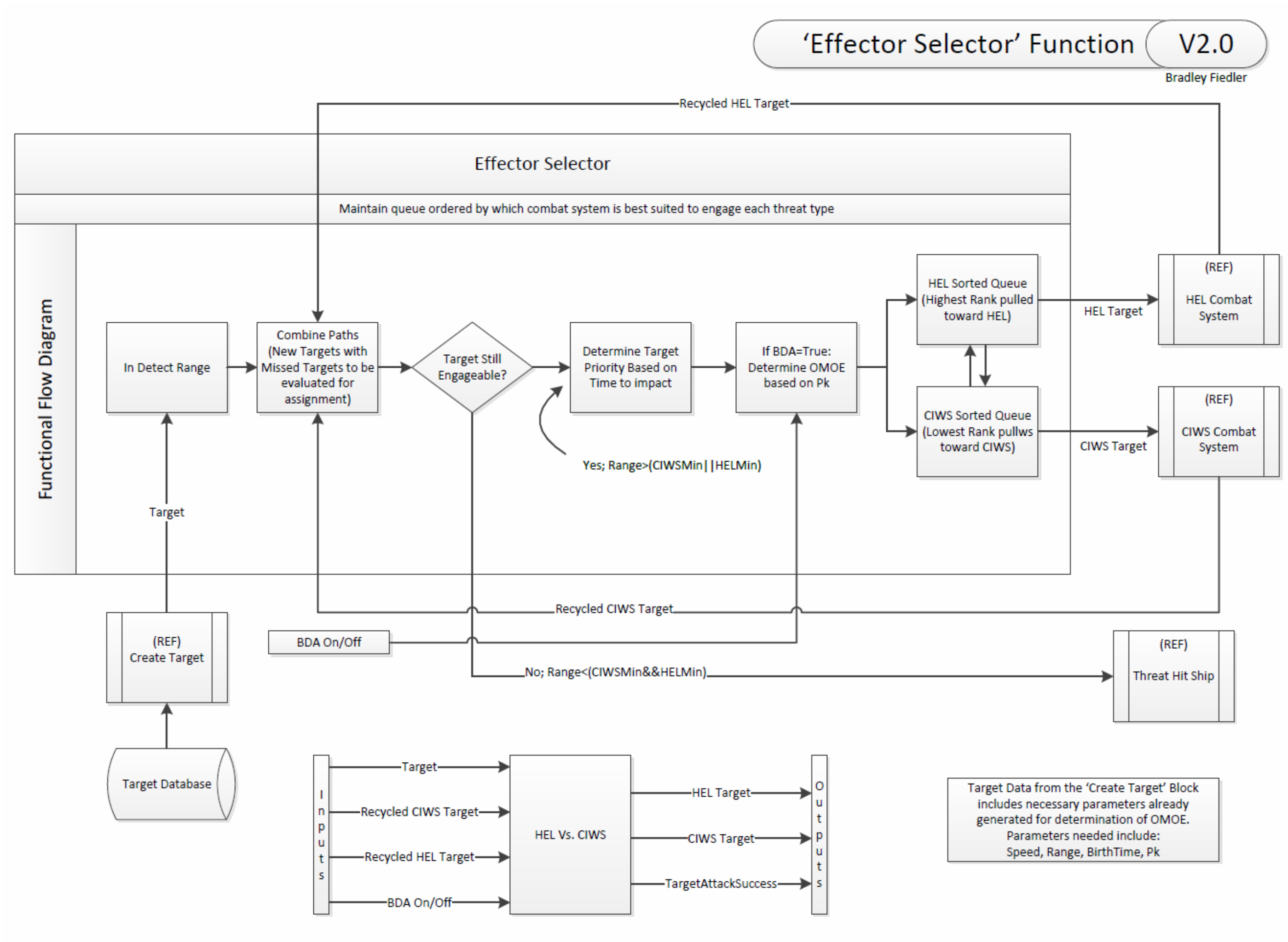


Figure 54. Weapon Selection FFBD

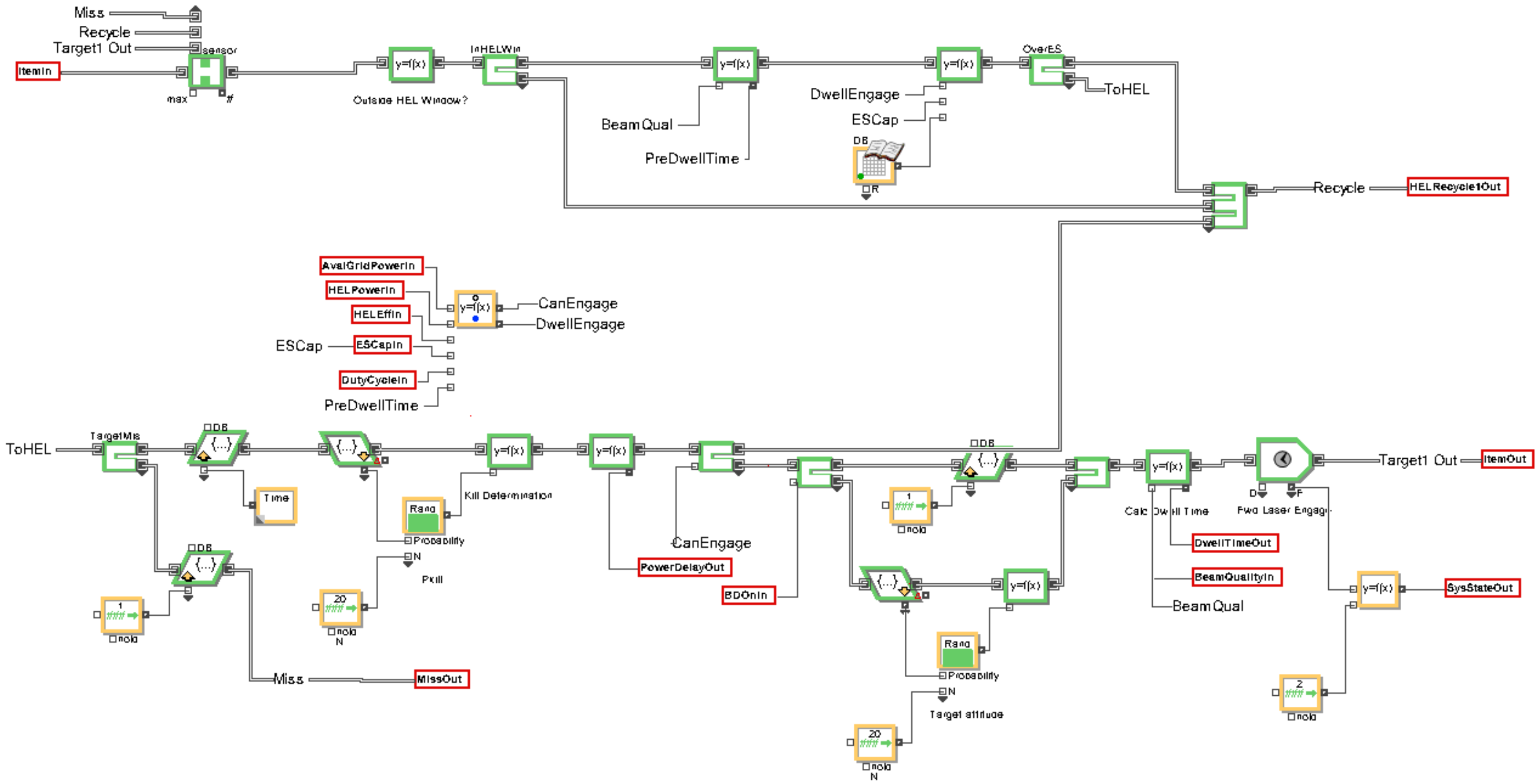


Figure 55. HEL Firing Solution

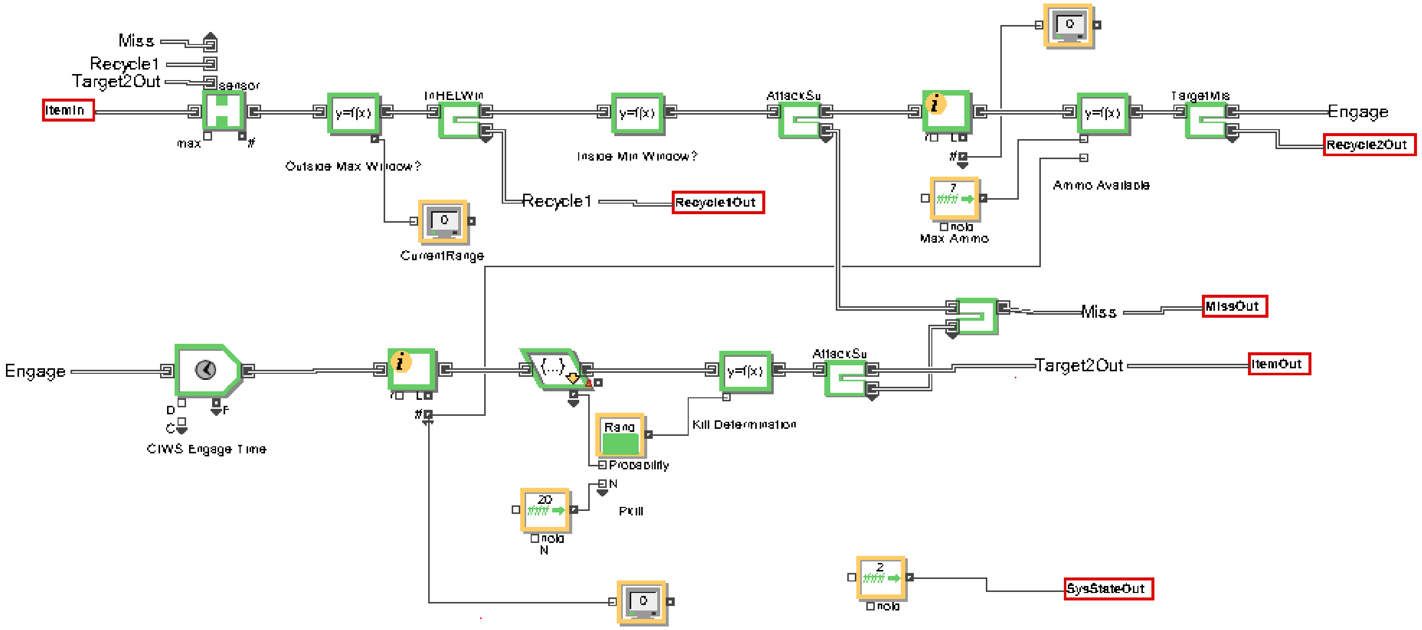


Figure 56. CIWS Firing Solution

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APPENDIX C. TRADE STUDY OF THE FREE ELECTRON LASER AND THE LASER WEAPON SYSTEM

To support an analysis of the Battle Damage Assessment system integration on a HEL Combat System in Chapter VI, a trade study was performed to compare the FEL versus the LaWS. This trade study reinforced the selection of the LaWS for the model and simulation and is the likely choice for the Battle Damage Assessment integration design approach.

Table 28. FEL vs. LaWS Trade Study (after ONR 2008)

System	Free Electron Laser System (FELS)	Laser Weapon System (LaWS)
System Integrator	Office of Naval Research with several Naval research organization	Directed Energy Warfare Office (DEWO): System Integrator Naval Research Laboratory and Pennsylvania State University Electronic-Optic Center: Laser designer Raytheon: CIWS integration effort
Beam Power	14.7 kW	33 kW by incoherently combining six laser beams
Beam Quality	~1	17
Wall-Plug Efficiency	10 %	25 %
Wavelength	Tunable Wavelengths	1.064 µm
Power Requirement	10 MW	400 kW
Technical Readiness Level	4	5
Testing Progress	Laboratory Testing	Tested in Sea Environment

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APPENDIX D. DEPARTMENT OF DEFENSE TECHNOLOGY READINESS LEVELS

Technology Readiness Levels are the metric to assess technology maturity. The using of TRL started with National Aeronautics and Space Administration (NASA) in the 1980s. The levels span the earliest states of scientific investigation (Level 1) to the successful use in a system (Level 9). TRLs are not a measure of validity; they indicate a level of maturity at the time of measurement (Department of Defense 2009, C-3). The U.S. Department of Defense uses the following TRLs to characterize the developmental status of DEW technologies.

Table 29. Hardware TRL Definitions, Descriptions, and Supporting Information (from Department of Defense 2009, C4–C5)

TRL	Definition	Description	Supporting Information
1	Basic principles observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied R&D Examples might include paper studies of a technology’s basic properties.	Published research that identifies the principles that underlie this technology. References to who, where, when.

TRL	Definition	Description	Supporting Information
2	Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.	Publications or other references that outline the application being considered and that provide analysis to support the concept.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.	Results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. References to who, where, and when these tests and comparisons were performed.
4	Component and/or breadboard validation in a laboratory environment.	Basic technological components are integrated to establish that they will work together. This is relatively “low fidelity” compared with the eventual system. Examples include integration of “ad hoc” hardware in the laboratory.	System concepts that have been considered and results from testing laboratory scale breadboard(s). References to who did this work and when. Provide an estimate of how breadboard hardware and test results differ from the expected system goals.

5	Component and/or breadboard validation in a relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components.	Results from testing a laboratory breadboard system are integrated with other supporting elements in a simulated operational environment. How does the "relevant environment" differ from the expected operational environment? How do the test results compare with expectations? What problems, if any, were encountered? Was the breadboard system refined to more nearly match the expected system goals?
6	System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.	Results from laboratory testing of a prototype system that is near the desired configuration in terms of performance, weight, and volume. How did the test environment differ from the operational environment? Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
7	System prototype demonstration in an operational environment.	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, in a vehicle, or in space).	Results from testing a prototype system in an operational environment. Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?

8	Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation (DT&E) of the system in its intended weapon system to determine if it meets design specifications.	Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate. Assessment of whether it will meet its operational requirements. What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before finalizing the design?
9	Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E). Examples include using the system under operational mission conditions.	OT&E reports.

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